Archean Geology
of an area between
Knife Lake and Kekekabic Lake,
eastern Vermilion district, northeastern Minnesota

A Thesis

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By

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ABSTRACT

Sedimentary and volcanic rocks of the Kekekabic Lake area, which is located within the eastern Vermilion district, northeastern Minnesota, comprise a portion of the Lower Precambrian Knife Lake Group and lie in three of Gruner's (1941) structural segments.

The dominant lithology within the Knife Lake greenstone segment is arkose. The arkose is largely composed of plagioclase feldspar, is approximately 250 feet thick, and underlies the Amoeba Lake member of the Knife Lake Group. Interbedded with the arkose is black slate. Rocks within the Knife Lake greenstone segment trend N 74^{o}E and dip 60^{o} to the southeast.

The dominant lithology within the Spoon Lake segment is graywacke. The graywacke samples studied are equally divided between the lithic and feldspathic subtypes. Rock fragments within the lithic graywackes are predominantly andesite and dacite. Plagioclase is the predominant feldspar within the feldspathic graywackes. Interbedded with the graywackes are green slates, mafic (basalt or andesite) crystal tuffs, volcanogenic conglomerate, and very minor iron-formation. The rocks within the Spoon Lake segment are approximately 800 feet thick, and have been deformed into a syncline which trends S 45^{o}W and plunges 35^{o} to the southwest.

The dominant lithology within the Kekekabic Lake segment is graywacke. The graywacke samples studied are equally divided between the lithic and feldspathic subtypes. Lithic and feldspathic graywackes of the Kekekabic Lake segment are similar petrograph-

ically to lithic and feldspathic graywackes of the Spoon Lake segment. However, the graywacke samples of the Kekekabic Lake segment, in general, contain more detrital K-feldspar (although it is still a minor component) and hornblende grains than those of the Spoon Lake segment. Interbedded with the graywackes of the Kekekabic Lake segment are green slates, mafic (basalt or andesite) and felsic (trachyte to latite) crystal tuffs, and very minor iron-formation. Graywackes and associated interbedded rocks of the Kekekabic Lake segment are approximately 1000 feet thick, and have been deformed into a syncline which trends S 50^{o}W and plunges 30^{o} to the southwest. The graywackes and associated interbedded rocks contained in both the Spoon Lake and Kekekabic Lake segments comprise the Amoeba Lake Member of the Knife Lake Group (Gruner, 1941).

The eastern portion of the Kekekabic Lake syncline is occupied by three subaerial flows. The oldest of these flows, stratigraphically, is a porphyritic green augite-hornblende andesite which is exposed at the nose of the syncline and is approximately 225 feet thick. To the west, the augite-hornblende andesite is conformably overlain by a red porphyritic hornblende andesite which is approximately 300 feet thick. The red hornblende andesite is overlain conformably, to the west, by a green porphyritic hornblende basalt which is approximately 300 feet thick.

The three subaerial flows apparently plunge under a green hornblende-rich tuff and agglomerate unit. The tuff is composed exclusively of hornblende grains and is bedded and cross-bedded. The agglomerate clasts are accidental lamprophyre rock fragments.

The hornblende-rich tuff and agglomerate is approximately 200 feet thick. The tuff and agglomerate and the three subaerial flows comprise the Kekekabic Lake Member of the Knife Lake Group (Gruner, 1941).

Turbidite sequences within the Kekekabic Lake area are characteristic of distal turbidites, and correspond to facies associated with the depositional lobe of the mid-fan portion of a submarine fan (Walker and Mutti, 1973).

Two periods of deformation have occurred in the Kekekabic Lake area along with broad folding and longitudinal and transverse faulting. The first period of deformation produced isoclinal folds, trending S 45^{o}-50^{o}W, with vertical to overturned fold axes that plunge to the southwest. The second period of deformation produced a pervasive N 62^{o}-70^{o}E cleavage throughout the area. Subsequently, broad folding warped the beds of the eastern Vermilion district on an axis trending N 60^{o}W. Following folding, longitudinal faulting divided the Kekekabic Lake area into three distinct segments. Concurrent with or subsequent to longitudinal faulting, transverse faulting locally offset rock contacts.

Sedimentary and volcanic rocks of the Kekekabic Lake area are representative of the middle portion of a calc-alkaline basalt-andesite-rhyolite volcanic pile accumulation which presumably developed within an island arc or continental orogenic system.

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Location

The area of study is located in the Boundary Waters Canoe Area of the Superior National Forest and is approximately 42 miles northwest of Grand Marais, Minnesota (Fig. 1). It consists of about 6 square miles in Lake County, Minnesota and lies between Kekekabic Lake to the south, Knife Lake to the north, Eddy Lake to the east, and a western boundary approximately determined by the portages between Bonnie, Spoon and Pickle lakes. Most of the area lies within T. 65N., R. 7W., and R. 6W. of the Kekekabic Lake 7.5 minute quadrangle, with a small portion in the Ogishkemuncie Lake quadrangle to the east.

The area is most readily accessible via the Seagull Lake port of entry at the end of the Gunflint Trail. It is approximately a 12-mile canoe trip from the Seagull Lake landing west-southwest to Eddy Lake on the northeast edge of the map area.

Statement of Problem

The Kekekabic Lake area contains metasedimentary and metavolcanic rocks of the Lower Precambrian Knife Lake Group. Interstratified within these rocks is a hornblende andesite unit. This unit was mapped as Ely greenstone by Clements (1903), but Gruner (1941) noted that it appears fresher than the ellipsoidal greenstones and suggested that it may be younger. Intrusion of the Saganaga Tonalite to the northeast and its subsequent unroofing

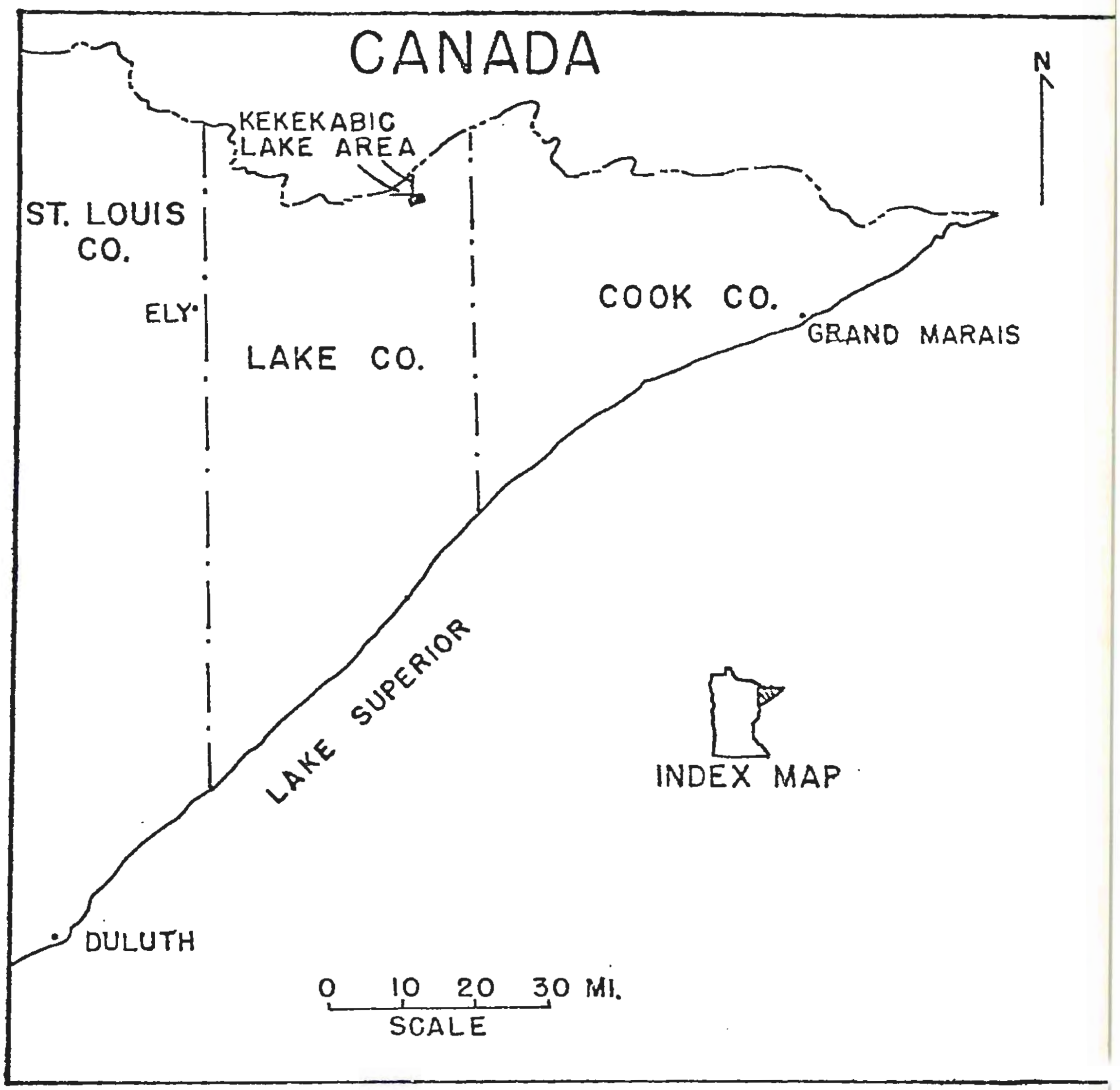

Figure 1: Location map of the Kekekabic Lake area, Lake County, Northeastern Minnesota.

also contributed detritus to the surrounding rock units. In addition to being stratigraphically complex, these rock units are also structurally complex. Gruner's (1941) geologic map indicated several periods of folding have occurred in the area, along with major longitudinal faulting which separated the area into discrete segments.

The objectives of this study were: 1) to determine if the volcaniclastic sediments in the area contain true pyroclastic material, with an emphasis being placed on how these volcaniclastics interfinger with tonalite-bearing conglomerates derived from the Saganaga Tonalite to the east; such a relationship would indicate whether there was penecontemporaneous volcanism and unroofing of the Saganaga Tonalite as assumed by Ojakangas (1972); 2) to produce a detailed geologic map of the area which lies in three of Gruner's (1941) structural blocks; and 3) to find evidence indicating whether the hornblende andesite unit is a high-level intrusion or a subaerial flow.

Previous Work

The Kekekabic Lake area was first studied by Grant (1892) who did detailed mapping of the area while he was a member of the Geological and Natural History Survey of Minnesota. He provided a description of the rock units surrounding Kekekabic Lake which included, "an anomalous green schist, a hornblende porphyrite, and an augite-soda granite." He also did detailed work, both microscopical and regional, on the augite-soda (Kekekabic) granite, which lies along the south shore of Kekekabic Lake.

Winchell, in the Geology of Minnesota, vol. IV of the Final Report (1899), gives brief descriptions of the rock units within the Kekekabic area and their gross relationships. This was included as part of his subsequently completed effort to produce a geologic map of Minnesota by mapping on a county-by-county basis. He also summarized the structual geology of Minnesota in vol. V of the Final Report (1900), along with providing rock descriptions of samples collected.

Clements (1903) summarized the complete stratigraphic, structural and petrographic knowledge of the Vermilion iron-bearing district of Northern Minnesota. The Kekekabic Lake area was interpreted as consisting of Ogishke conglomerate along the north shore of Kekekabic Lake; Knife Lake Formation between Kekekabic and Knife lakes; and Ely greenstone in the vicinity of Eddy Lake (Fig. 2). The Ely greenstone was thought to represent a major cross-folding of the east-west trending greenstone belts. The cross-folding resulted in, "anticlinal boss-like areas plunging down under the sediments and completely surrounded by them."

Van Hise and Leith (1911), working for the United States Geological Survey, included Clements' (1903) work on the Vermilion iron district with work done on the iron-bearing districts of Wisconsin and Michigan to produce a regional view of the geology surrounding Lake Superior.

Stark (1927) mapped the rock units surrounding Kekekabic Lake, including the present area of study, as a doctorate thesis project. He provided detailed descriptions (both megascopic and microscopic) of the rocks involved. He also did work on the primary structure

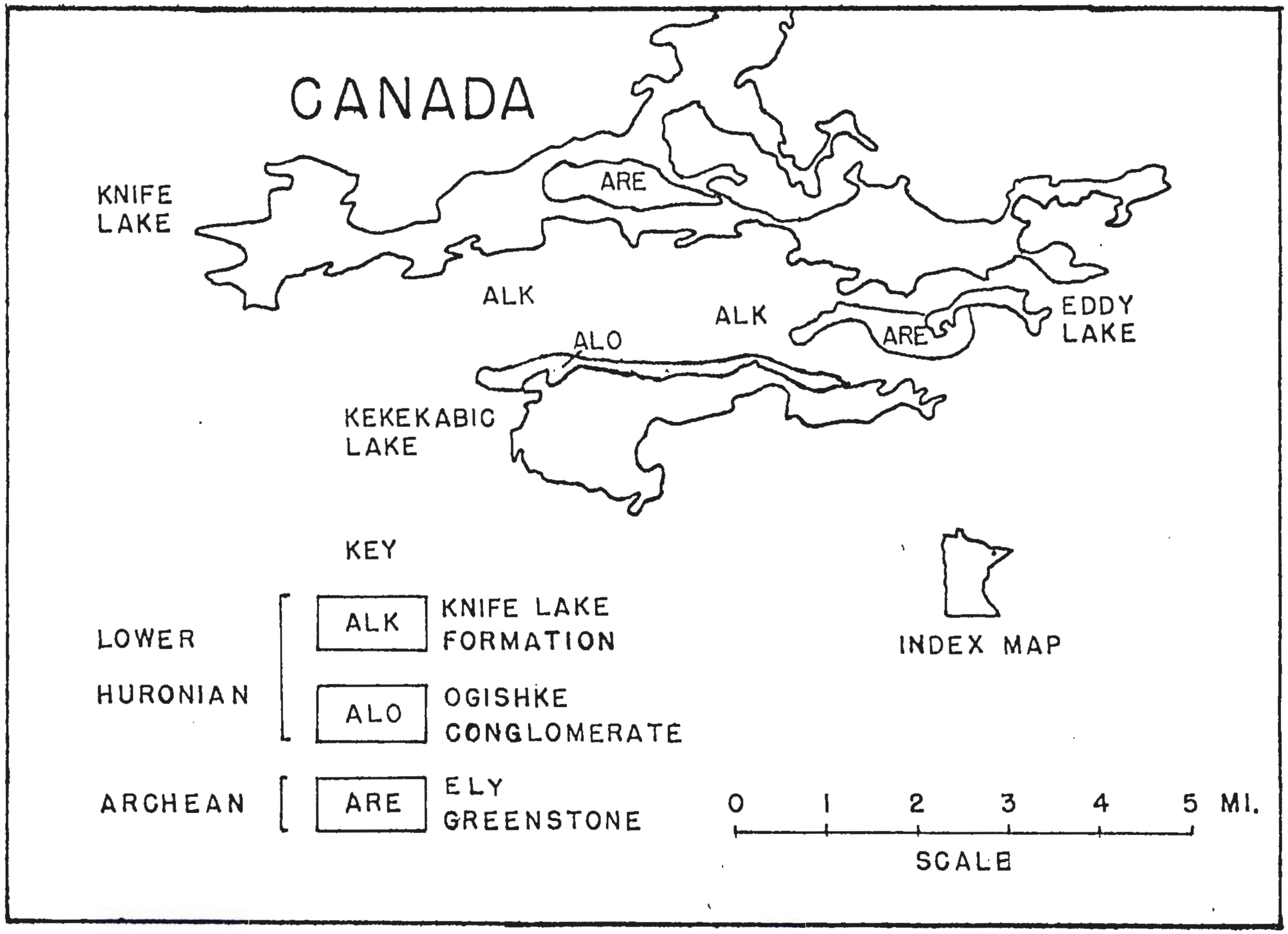

Figure 2: Early geologic map of the present study area (after Clements, 1903).

of the Kekekabic granite and determined from petrographic and structural evidence that the granite is a satellite of the Snowbank Lake batholith. In 1929, Stark commented on the origin of the Agawa iron-bearing formation which occurs in the Kekekabic Lake area as discontinuous outcrops of banded slates which contain alternating ferruginous bands 2 to 3 centimeters in width.

Stark and Sleight (1939) reviewed the stratigraphy of the Knife Lake Group in the Kekekabic-Ogishkemuncie Lake area. This was a continuation of work that was started under Grant in 1924.

Gruner (1941) provided a major structural interpretation of an area within the eastern part of the Vermilion district, centered around Knife Lake. He determined that major longitudinal faults divide the district, as a whole, into fault-bounded structural segments (Fig. 3). Three of these (the Kekekabic Lake, Spoon Lake and Knife Lake greenstone segments) lie in the present area of study. According to Gruner, it is very difficult to correlate stratigraphy from one segment to another, indicating each of these structural segments is distinct in itself. During his 13 summers of mapping the area, Gruner was also able to divide the Knife Lake Group into 21 separate lithologic units. Included in this division was one unit exposed in the Kekekabic Lake area. It was called the "Kekekabic Lake tuffs, agglomerates, slates and andesite porphyry."

Ojakangas (1972a, 1972b) did a general study of the volcanogenic sediments within the Vermilion district. His study provided a detailed description of the graywackes within the Vermilion district including their megascopic and microscopic characteristics. Some of his samples were taken from the present area of study.

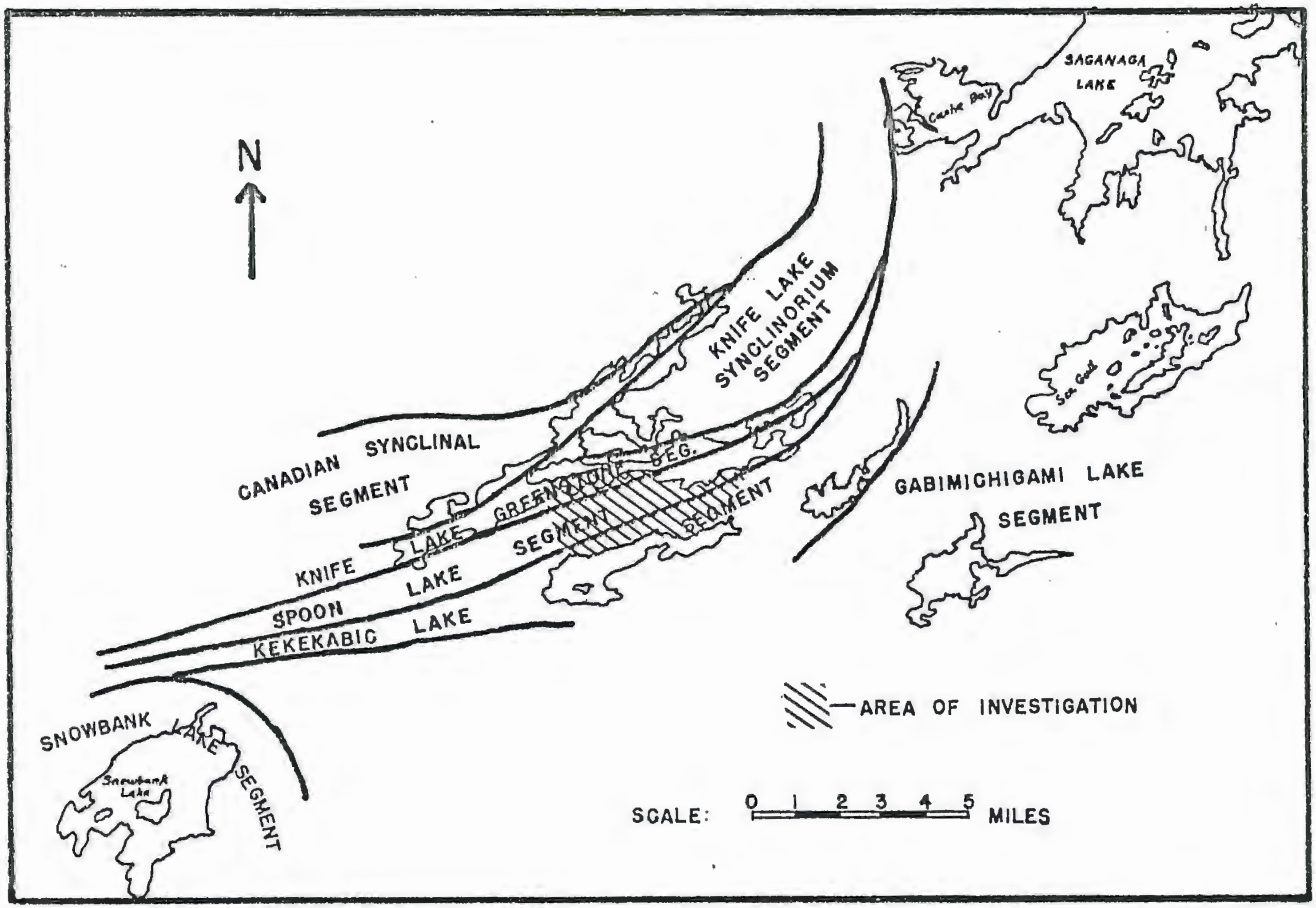

Figure 3: Structural segments of the Knife Lake Group, eastern Vermilion district (after Gruner, 1941).

Methods of Study

Twenty-three days during the summer of 1977 were spent in the field mapping the area, with five days during the spring of 1978 used to recheck paleocurrent measurements and collect more samples for petrographic study. Shoreline areas were mapped by canoe while pace and compass was used across land. Mapping was done on a scale of 1/24,000 throughout the area using 7.5 minute quadrangle base maps. The objectives of the field mapping were to: 1) examine all the outcrops in the area; 2) sample the rock units involved; and 3) take strike and dip, cleavage, lineation, and cross-bedding measurements where possible. Plate 1 is a geologic map of the area.

A total of 149 rock samples were collected, with 90 studied petrographically. Modal analyses were accomplished by counting 600 points per thin section. Slabs were stained for potassium feldspar content. Selected samples were also studied by heavy mineral and x-ray analyses. Whole rock chemical analyses were obtained on two porphyritic hornblende andesite samples and one hornblende tuff sample. Strike and dip, as well as cleavage measurements were contoured on stereonets by computer to aid in structural interpretation of the area. Cross-bed and lineation measurements were rotated on a stereonet to give original current directions and original structural attitudes, respectively.

Acknowledgements

Thanks is given to Dr. Richard W. Ojakangas, University of Minnesota, Duluth, who served as thesis advisor on this project, and who in particular met the author in the field and established order and direction to the field mapping. Thanks is also given to Dr. J. C. Green, who contributed his expert petrographic knowledge and suggestions to this project; and to Dr. D. M. Davidson, Jr., who ably assisted in interpretation of the structural data. A special thanks is given to Jan (my wife), who served as field assistant during the field mapping of 1977; and to Dave Jones who assisted on the return trip into the area during 1978.

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REGIONAL GEOLOGY

Introduction

The Kekekabic Lake area of Northeastern Minnesota lies in the eastern portion of the Vermilion district. The Vermilion district, as defined originally by Clements (1903), is a narrow belt of metavolcanic and metasedimentary rocks, 100 miles long and 5 to 10 miles wide, that extends from the vicinity of Tower, near Lake Vermilion, northeastward to the International boundary in the vicinity of Saganaga Lake (Fig. 4). The metavolcanic-metasedimentary sequence is bounded on the north by the Vermilion granite-migmatite massif, on the south by the Giants Range batholith, and on the east by the Saganaga batholith. These younger, enclosing granitic rocks have been dated in the range of 2,400 to 2,750 million years, which brackets the Algoman orogeny (Goldich, 1968). Much of the eastern part of the district is truncated by the Duluth Complex of Keweenawan age (1,100 million years).

The metavolcanic-metasedimentary sequence in the district is a complex volcanic pile accumulation, deposited mainly in a subaqueous environment. This sequence is analogous to greenstone complexes of Canada (Goodwin, 1968), the Vermilion district being the westward extension of the Wawa Greenstone Belt of Ontario (Riley and others, 1971).

The rocks within the district trend eastward and northeastward with generally steep dips. Folding of at least two generations was broadly contemporaneous with emplacement of the fringing

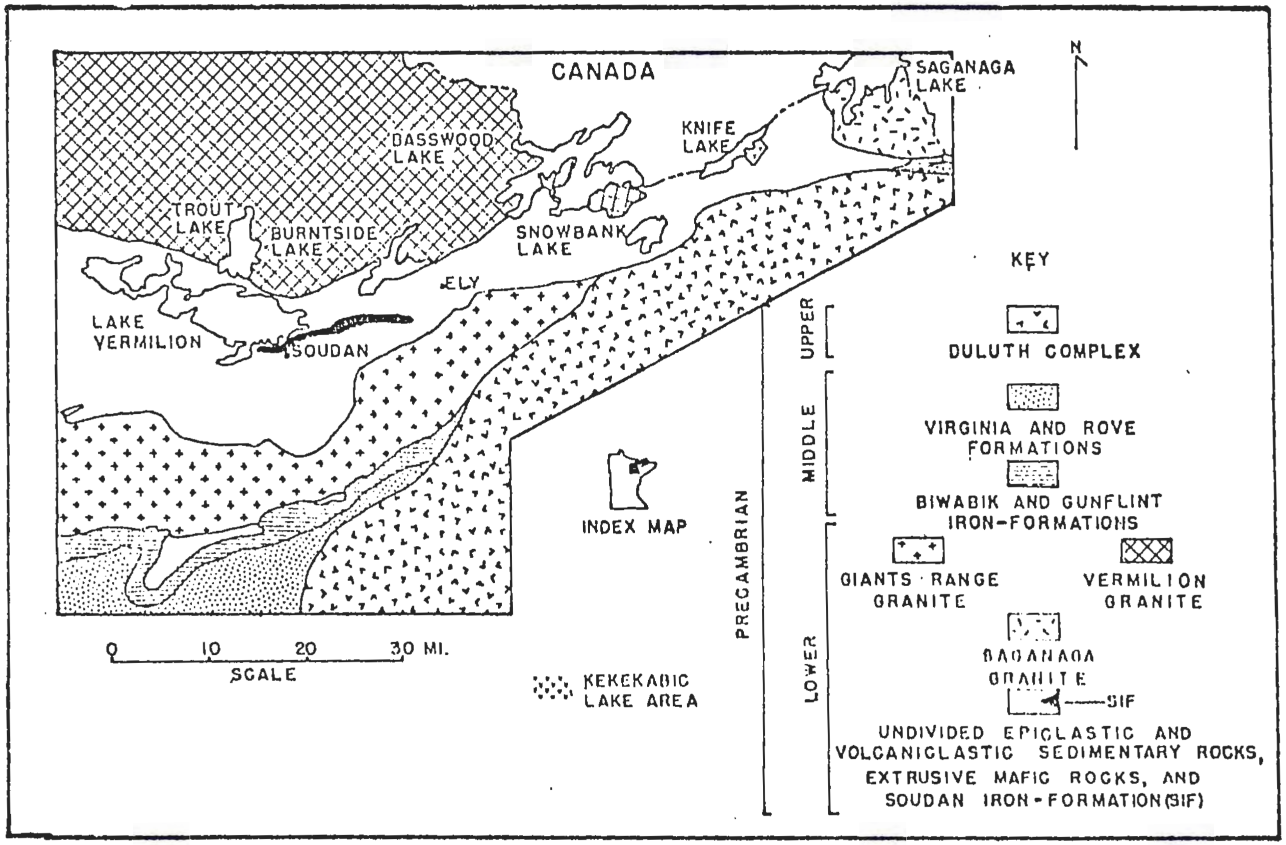


Figure 4: General geologic map of the Vermilion district (after Sims, 1972).

batholithic rocks and was followed by a major period of regional faulting (Sims, 1972).

Stratigraphy

According to Sims (1972), the oldest exposed rocks at any particular locality within the Vermilion district are, in general, mafic metavolcanic rocks (Fig. 5). Many of the lavas are pillowed indicating deposition in water. Lenses of banded iron-formation occur within the dominant volcanic successions, particularly in the upper parts. The mafic volcanic rocks attain a minimum thickness of 12,000 feet in the Vermilion district (Green, 1970) and give way rather abruptly upward to felsic volcanics, including abundant pryoclastic deposits. These rocks grade upward and laterally into graywacke-type metasedimentary rocks which are dominantly graywacke-slate, but include substantial amounts of felsic volcaniclastic rocks, local mafic flows, and some conglomerate and iron-formation (Sims, 1972). The felsic volcanic successions tend to be thinner than the mafic successions, having a maximum thickness of 2,500 feet within the Vermilion district, whereas the sedimentary successions attain thicknesses of as much as 5,000 feet (Green, 1970).

The stratigraphy of the Vermilion district closely parallels other Archean volcanic-sedimentary greenstone belts of the Canadian shield. Goodwin (1968) described the typical Archean assemblage as consisting of a thick, complex volcanic-sedimentary pile accumulation (Fig. 6). The volcanic-sedimentary pile probably evolved by: 1) formation of a mafic platform followed by; 2) predominantly pyroclastic eruption of material of calc-alkaline

		1941 E. Vermilion district (Cruner)
	Keweenawan	Duluth Gabbro Diabase intrusions
	Animikie Series	Rove Slate Gunflint Fm.
		Unconformity
Algonkian System	Algoman Series	granites, syenites hornblendite feldspar porphyry
	Knife Lake Series	graywacke, slate tuff, conglomerate, etc. (21 units)
		Unconformity
Archean System	Laurentian Series	Saganaga Granite acid intrusive/extr.
	Keewatin Series	Soudan Iron Fm. sediments & pyroclastics andesite intr. Ely Greenstone

		1978 Kekekabic Lake Area (Present Study)
Upper Precambrian		Diabase dikes
		Unconformity
Lower Precambrian		Kekekabic Granite?
	Knife Lake Group	Kekekabic Lake Member Amoeba Lake Member massive arkose
		Unconformity
		Saganaga Tonalite
		Ely Greenstone?

Figure 5: Stratigraphic column of the eastern Vermilion district and the Kekekabic Lake area

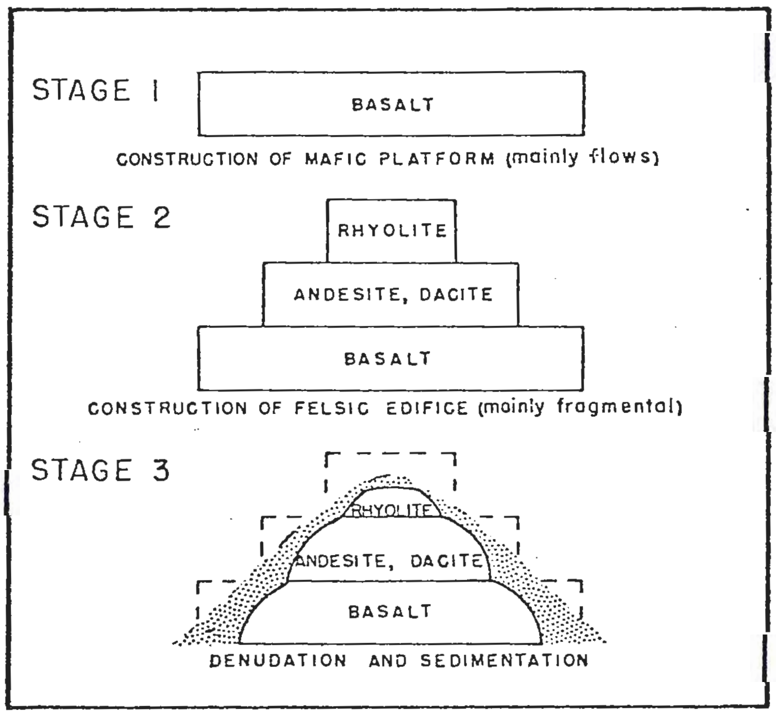


Figure 6: Evolution of an Archean volcanic-sedimentary pile (after Goodwin, 1968).

chemical affinity leading to erection of numerous high-rising piles resting upon the platform; and 3) an erosional stage marked by denudation of the volcanic piles and construction of thick volcanogenic-sedimentary successions. These mafic-to-felsic volcanic sequences may be repeated in time and space, with lateral gradations rapid in and adjacent to the volcanic pile. The total stratigraphic thickness of the pile is commonly on the order of 30,000 feet.

The Saganaga batholith intruded the metavolcanic-metasedimentary sequence of the eastern Vermilion district and was unroofed and eroded during Knife Lake time. This is indicated by the presence of clasts of Saganaga Tonalite in the conglomerate units interbedded with graywackes and tuffs of the Knife Lake Group (e.g., McLimans, 1972; Ojakangas, 1972b). Penecontemporaneous with the intrusion of the Saganaga batholith was the emplacement of the Vermilion granite-migmatite massif to the north of the Vermilion district and the Giants Range batholith to the south (Sims, 1972). These latter two batholiths also transect the metavolcanic-metasedimentary sequence of the Vermilion district but apparently were not unroofed. Emplacement of all three batholiths probably was at relatively shallow depths. This is indicated by: 1) narrow thermal aureoles; 2) geophysical evidence; and 3) unroofing of the Saganaga batholith. Late Algoman faulting has locally deformed all three batholiths (Sims, 1972).

Intrusion of the Upper Precambrian Duluth Complex along the eastern edge of the Vermilion district led to metamorphism of the Giants Range batholith and the metavolcanic-metasedimentary rocks.

Adjacent to the contact, mineral assemblages within the Giants Range batholith are characteristic of the transition zone between the hornblende-hornfels facies and the pyroxene-hornfels facies (Green, 1970); within the metavolcanic-metasedimentary rocks, granulite-facies assemblages are locally attained (Sims and others, 1972).

In the Kekekabic Lake area, the oldest known strata (Fig. 5) consist of massive arkose and graywacke which are overlain by graywackes, slates, and tuffs of the Amoeba Lake member of the Knife Lake Group (Gruner, 1941). The thickest sequence of sediments in this member, about 4,000 to 5,000 feet, is found in the segment of the Knife Lake synclinorium whose axis passes through Amoeba Lake (Amoeba Lake lies to the north of Knife Lake). The Amoeba Lake member is overlain by tuff, agglomerate, and andesite porphyry of the Kekekabic Lake member of the Knife Lake Group. Gruner (1941) estimated the rocks within this latter member to be 2,000 to 4,000 feet thick.

A thin, patchy veneer of glacial deposits covers some areas in the eastern Vermilion district, but rarely reaches a thickness of more than a few feet (Gruner, 1941).

Lithologies

Ely Greenstone

Van Hise and Clements (1901) named the Ely greenstone from exposures at and near the town of Ely (Fig. 4), which include extrusive, intrusive, and fragmental rocks that are various shades of green because of contained secondary chlorite, amphibole, and epidote. Rocks of basaltic composition comprise well over 90 percent of the Ely greenstone (Morey and others, 1970). Intermediate to felsic volcanic rocks and hypabyssal intrusive rocks, banded iron-formation and chert, and metasedimentary rocks constitute the remainder. The basalt occurs dominantly as flows, most of which are pillowed. Intrusive metadiabase is associated with the flows as concordant and discordant bodies probably representing shallow intrusives or feeder bodies. Fragmental rocks of intermediate composition are widespread in the western part of the district and range texturally from tuff-breccia to tuff.

Soudan Iron-formation

The Soudan Iron-formation was named by Van Hise and Clements (1901) from exposures at Soudan Hill, near the town of Soudan (Fig. 4). At the type locality this formation consists of fine-grained ferruginous cherts with minor amounts of interbedded fine-grained clastic rocks and metabasalts (Morey and others, 1970). The clastic rocks are mainly siliceous sericitic phyllites and carbonaceous slates. Locally, these rocks are intruded by mafic dikes and felsic porphyries.

Knife Lake Group

The Knife Lake Group (Knife Lake Series of Gruner, 1941) was first used by Grout in 1933 for rocks that are typically exposed around Knife Lake, near the International boundary (Fig. 4), and which were previously called Knife Slates (Van Hise and Clements, 1901), or Knife Lake Slates (A. Winchell, 1888; Clements, 1903). Gruner (1941) divided the Knife Lake Group into 21 lithologic members. Most of the rocks within the group are epiclastic or volcaniclastic with all showing evidence of a volcanogenic origin. These rocks, in approximate order of decreasing abundance, are graywacke, slate, agglomerate, conglomerate, and tuffaceous sandstone (Ojakangas, 1972b). Igneous rocks, which are a minor but integral part of the group, include basalt flows and intrusions and porphyritic andesites, which are either flows or intrusive rocks. The Knife Lake Group cannot be traced westward into the Lake Vermilion area but is correlated with the Lake Vermilion Formation (Fig. 7). The Lake Vermilion Formation is composed of epiclastic and volcaniclastic rocks exposed in the vicinity of Lake Vermilion. The Knife Lake Group is overlain by the Newton Lake Formation in the central part of the Vermilion district. The Newton Lake Formation consists of mafic metavolcanic and felsic to intermediate rocks.

Amoeba Lake Member

Gruner (1941) referred to this unit as containing graywackes, slates, and tuffs which were only slightly different from the graywackes and slates exposed around Knife Lake in that the Amoeba Lake Member contained more graywacke and considerable tuffaceous material. Lenses of conglomerate consisting of pebbles of all varieties of previously described rocks are interstratified. Graded bedding is common.

Kekekabic Lake Member

The tuff and agglomerate contained in this unit were referred to by Gruner (1941) as green rocks which disintegrated to a beautiful light-green sandy material consisting chiefly of hornblende. The tuff within this unit is bedded while the agglomerate consists

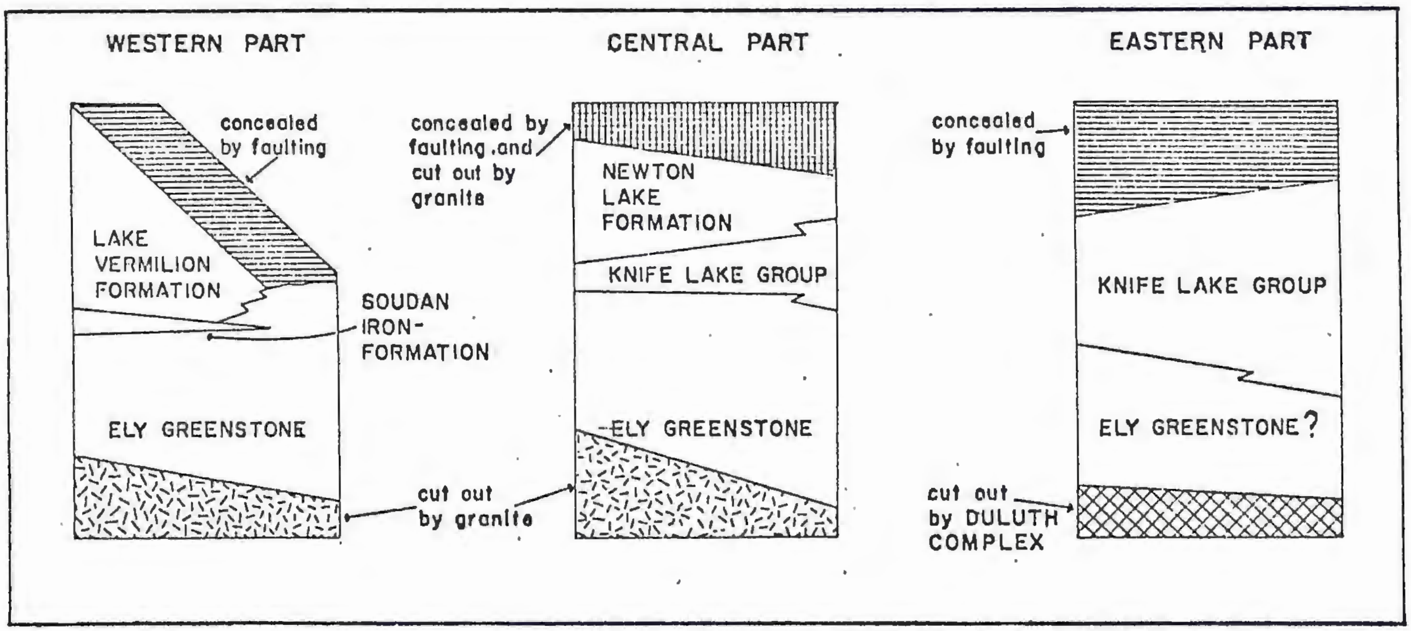


Figure 7: Principal lithologies of the Vermilion district (after Sims, 1972)

of fragments from 0.5 to 25 centimeters in diameter. The fragments may be well-rounded or very angular, and according to Gruner, usually are pieces of andesite porphyry or tuff with conspicuous hornblende phenocrysts. The andesite porphyry within this unit was first described petrographically by Grant in 1892. He referred to it as a "porphyryte" containing an aphanitic groundmass which varied in color from a reddish purple to a dull olive green with the freshest and more abundant phases showing the purple color. In the groundmass were sharply outlined shining black crystals of hornblende and also irregular greenish areas. It was thought by Stark (1927) that this mass of porphyryte was a part of the same magma which produced the volcanic tuff on the north side of Kekekabic Lake, but that it solidified before reaching the surface. Gruner (1941) determined the porphyry lies in a syncline because the beds south of the mass top north and the beds north of the porphyry top south. This syncline continues westward beyond the limits of the porphyry. Within the Kekekabic Lake area, graded bedding and excellent cross-bedding are common and make interpretation of the structure certain (Gruner, 1941).

Saganaga Batholith

The Saganaga batholith, at the extreme eastern end of the Vermilion district, is a composite intrusion containing several rock types (Hanson and Goldich, 1972). The dominant phase is a gray, medium- to coarse-grained tonalite, although the composition ranges from a felsic pink or red tonalite, where sheared, to granodiorite and hornblende diorite at its margin. It is characterized by large (commonly 1 centimeter across) quartz aggregates that resemble phenocrysts, informally known as quartz eyes. The tonalite intrudes greenstone and gneiss on the south, north, and east, and is overlain unconformably along the western margin by metaconglomerate and associated metasedimentary rocks of the Knife Lake Group.

Duluth Complex

The Duluth Complex, formerly called the Duluth Gabbro Complex (Taylor, 1964), is a composite body consisting of several anorthositic, gabbroic, and granitic intrusions. The oldest rocks of the Duluth Complex are in Northern Cook County and comprise a sequence of southward dipping, relatively thin, sheet-like intrusions of gabbroic composition. These rocks are transected to the west by anorthositic rocks containing 80 to 99 percent calcic labradorite. Intrusive into the anorthositic rocks are troctolitic rocks of several varieties, which locally contain layers and lenses of picrite, dunite, norite, olivine gabbro, and ferrogabbro. The troctolitic rocks occur along the base of the complex. Felsic and intermediate rocks, including granophyric granite, occur discontinuously along the top of the complex as small plutons and relatively flat-lying sheets. The Duluth Complex was intruded along an unconformity between the overlying volcanic rocks of the Keweenawan North Shore Volcanic Group and underlying rocks of Lower and Middle Precambrian ages.

Diabase Dikes

Gruner (1941) described these as brown on the weathered surfaces and almost black where fresh. They are medium- to fine-grained although very fine-grained contact zones 2 to 5 centimeters wide are common. The dikes are rarely over 15 meters wide, generally 2 to 10 meters, and are commonly nearly vertical. Some of them are straight and can be followed for miles, but most are covered for considerable distances.

Quaternary Deposits

Glacial drift covers relatively few parts of the eastern Vermilion district and Gruner (1941) gives no description of Quaternary deposits. However, many outcrops, especially slates along the lake shores, show good glacially polished and grooved surfaces. In the Kekekabic Lake area, 31 measured striation directions plot between N 5^{o}E and N 35^{o}E. Associated chattermarks indicate glacial movement from the northeast.

Structure

Folds

In the western part of the Vermilion district, two generations of folding and a younger generation of deformation (including both faulting and kinking) have been recognized (Hooper and Ojakangas, 1971). The two generations of folding are referred to as the Embarrass-Lake Vermilion and the Tower generations (Sims, 1972). Similarly, in the eastern part of the district, at least two generations of folding can be inferred from Gruner's (1941) geologic map; however, their ages relative to the fold generations in the western part remain uncertain.

The metavolcanic-metasedimentary rocks in the eastern part of the Vermilion district trend northwest on the south side of the Saganaga batholith and northeast along its western margin.

The rocks on the south side of the Saganaga batholith are interpreted as having been folded during an older generation of folding, either prior to or contemporaneous with intrusion of the Saganaga batholith (Sims, 1972). They trend N 60^{o}-70^{o}W, and apparently are deformed by tight to close folds on northwest-trending axes. Gruner (1941) considered these folds as comprising the Agamok Synclinorium of the Gabimichigami Lake structural segment (Fig. 3). This northwest-trending folded segment is truncated on the northwest by a major fault that separates this segment from rocks folded on northeast-trending axes. These northeast-trending folds have been collectively referred to as comprising the Knife Lake Synclinorium and are interpreted as having been folded during or after emplacement of the Saganaga batholith (Gruner, 1941). The younger northeast-trending fold generation is by far the dominant type and overprints any older fold generations.

Faults

The strata within the Vermilion district are sliced into several structural belts or segments by high-angle longitudinal faults (Gruner, 1941; Sims and others, 1968). The principal faults trend in a general easterly or northeasterly direction and at places cut out substantial amounts of both the metavolcanic and metasedimentary sequence (Sims, 1972). The longitudinal faults in the eastern part of the district are subparallel to the strike of the rocks, making determination of vertical and horizontal displacement difficult. However, the difficulty in correlating the rocks from one fault block to another indicates the displacements were large, on the order of several miles horizontally and up to 10,000 feet vertically (Gruner, 1941). Several smaller transverse faults are known in the district. They generally have: 1) lesser displacements, both horizontally and vertically, than the longitudinal faults; 2) dominantly strike northeastward; 3) have left-lateral strike-slip displacements; and 4) mainly produce small or moderate offsets of rock contacts. The major episode of faulting within Northern Minnesota, including the Vermilion district, was concurrent with and subsequent to emplacement of the granite batholiths (Sims, 1972). The faulting, therefore, is considered to be a late phase of the Algoman orogeny.

Metamorphism

The rocks within the district dominantly contain mineral assemblages of the greenschist facies (Turner, 1968). Adjacent to the batholitic intrusions, including the Saganaga batholith in the eastern Vermilion district, and near some faults, amphibolite facies is reached (Sims, 1972).

PETROGRAPHY

Introduction

Detailed petrographic work on the metavolcanic and metasedimentary rocks of the eastern Vermilion district is lacking at the present time. Gruner (1941) divided the Knife Lake Group of the eastern Vermilion district into 21 lithologic members but only described the rocks megascopically.

Some recent workers in the eastern Vermilion district have sought to describe the rocks within the Knife Lake Group in petrographic detail. Ojakangas (1972a, 1972b) has completed a general petrographic study of samples collected throughout the eastern Vermilion district. McLimans (1971) studied four granite-bearing conglomerate units derived from the Saganaga Tonalite. Feirn (1977) studied Lower Precambrian metavolcanic and metasedimentary rocks within the Jasper Lake area while Severson (1978) has recently completed a petrographic study of graywacke and conglomerate units in the Ogishkemuncie Lake area (Jasper and Ogishkemuncie Lakes are to the east of Kekekabic Lake). The present study and one to the north by Duex (pending completion) will add more petrographic information to the work already completed.

The rocks within the Kekekabic Lake area are contained in three of Gruner's (1941) structural blocks. According to Gruner, each of these structural blocks is distinct in itself. Therefore, the petrography presented in this paper will be divided into three parts, each part corresponding to one of the three structural blocks.

Rocks within the Kekekabic Lake area are all metamorphosed to varying degrees, but the prefix "meta" is generally omitted in this paper.

Problems

The rocks in the present area of study, as well as the entire eastern Vermilion district, have been metamorphosed and deformed. In addition, many outcrops are badly weathered and covered with a blanket of moss and lichen. Therefore, recognition of distinct volcanic and/or sedimentary lithologies in the field is very difficult. For the purposes of this study, graywacke was considered to be the dominant lithology in the field and is here defined as as well bedded, dark green sandstone.

The best outcrops in the Kekekabic Lake area are along lakeshores. Inland areas are covered with a dense forest of deciduous and coniferous trees with an undercover of smaller plants. The few good outcrops inland occur as isolated islands surrounded by intervening swamp and forest, making lithologic and stratigraphic correlation between outcrops difficult. In addition, stratigraphic thicknesses were not measured in the field due to the lack of traceable marker beds.

Precise location of outcrops (Plate 1) along lake shorelines provided no problem, but location of outcrops within the heavily vegetated inland areas is at best imprecise.

Techniques

Field study of the rocks in the Kekekabic Lake area included:

1) location of the outcrop, 2) determination of the lithology (as best as possible), and 3) examination of the outcrop for: a) bedding planes from which to measure strike and dip, b) slaty cleavage for cleavage measurements, and c) any sedimentary feature such as graded beds, cross-beds, flame structures, or flute casts which would determine top direction, paleocurrent direction, or depositional environment.

Examination of graywacke outcrops included measurement of bed thicknesses, with actual bed-by-bed descriptions done on relatively clean, unweathered outcrops which expose several meters of section.

Operational definitions, Sedimentary rocks

In this paper, conglomerate is used for sedimentary rocks which contain rounded clasts greater than 2 mm in diameter. Sandstone refers to sedimentary rocks containing particles 0.2 to 2 mm in diameter while rocks that contain particles $<$0.2 mm in diameter are called slates (metamorphosed shale).

During the petrographic study of the samples collected from the Kekekabic Lake area, precise lithologic names were given to the sedimentary rocks according to the sandstone classification in Figure 8 (Pettijohn, 1957). According to the classification, graywacke is defined as a sandstone which contains more than 15% clayey matrix and abundant rock fragments and/or feldspar. Modal analyses showed some of the graywacke samples studied were subgraywackes while others were actually arkose. Obviously no distinction could be made in the field between graywacke and subgray-

Matrix Percent		Matrix > 15%		Matrix < 15%		
Sand Grains	Feld. > Rock Frg.	Sandstone	Feldspathic Graywacke	Arkose Sandstone		Orthoquartzite
				Arkose	Subarkose	
	Rock Frg. > Feld.	Graywacke	Lithic Graywacke	Lithic Sandstone		
				Subgray- wacke	Proto- quartzite	
	Quartz Percent	Variable, < 75%		< 75%	75-95%	> 95%

Figure 8: Classification used in this study for rocks containing sand-sized particles (after Pettijohn, 1957)

wacke. Therefore, for simplicity, the imprecise field term of graywacke will be used throughout this paper with the understanding that some subgraywackes are included.

Graywackes comprise over 50% of the sedimentary rocks studied. They are equally divided between the lithic and feldspathic subtypes. Arkose, conglomerate, and tuffs make up the remainder of the rocks studied.

Components (framework grains $>$ 0.03 mm) found in the petrographic study of the graywackes and related rocks include:

Undulose common quartz:	Clear unit grains; undulose extinction; anhedral; probably plutonic, but may be volcanic.
Volcanic quartz:	Clear unit grains; sharp extinction; no inclusions; some have sub- to euhedral, dipyramidal forms.
Polycrystalline quartz:	Composite grains with more than one extinction unit; undulose extinction; anhedral; probably plutonic, but may be metamorphic.
Plagioclase:	Partially or completely altered to sericite (some to carbonate); predominantly polysynthetically twinned; few zoned crystals; comparison of relief with common quartz indicates albite or albite-oligoclase.
Orthoclase:	Dusty alteration; poorly twinned (Carlsbad); hard to distinguish from untwinned plagioclase, therefore presence determined by staining with sodium-cobaltinitrate.
Hornblende:	Detrital crystals; generally unaltered; some identical to phenocrysts in volcanic rock fragments, however most are similar to hornblende-rich tuffaceous sediments; pleochroic in yellows and greens; tuffaceous sediments show zoned crystals with metamorphic (actinolite) overgrowths.

Chlorite:	Commonly spots in the matrix; pleochroic in green; "Berlin Blue" interference color (penninite).
Epidote:	Predominantly minute, dark colored spots in the matrix.
Opaques:	Dominantly magnetite; hematite, pyrite, and some leucoxene also present.
Carbonate:	Fine-grained, anhedral blebs found in matrix; also late euhedral rhombs.
Matrix:	Fine-grained interstitial material less than 0.03 mm in diameter; generally appears as a black, crystalline material containing hornblende, quartz, plagioclase, chlorite, epidote, minute rock fragments, and sericite.
Others:	Includes minute, unidentifiable crystals and rock fragments, quartz veinlets, and small aplite dikes.

According to Pettijohn's (1957) classification, lithic graywackes contain more detrital rock fragments than feldspar clasts. The lithic graywackes within the present area of study contain dominantly volcanic rock fragments. These volcanic rock fragments are angular and 0.5 to 1.0 mm in diameter with some up to 3.0 mm. Staining characteristics of the individual rock fragments were determined by staining the thin section heels with sodium-cobaltinitrate. A fragment observed under the petrographic scope could then be matched to the same fragment on the stained heel.

Of all the rock fragments studied, only rhyolite, dacite, andesite, basalt, recrystallized volcanic, and siltstone fragments are distributed throughout the entire study area. Hornblende andesite, hornblende trachyte-latite-trachyandesite, polycrystalline hornblende, plutonic, chert, and sericite phyllite rock fragments are only found locally. Petrographically the rhyolite, dacite, andesite, basalt, recrystallized volcanic, and siltstone fragments are described as follows:

Rhyolite

Rhyolite fragments are characterized by phenocrysts of quartz and/or orthoclase in a fine-grained, granular, K-feldspar-rich groundmass. Visual estimation of composition indicates approximately 15% K-feldspar phenocrysts, 15% quartz phenocrysts, and 70% groundmass consisting of quartz and K-feldspar. The rhyolite fragments take a deep yellow stain.

Volumetrically the rhyolite fragments comprise 5% of all the rock fragments studied. They account for 1% of all the framework grains studied with the amount of rhyolite fragments present in any one thin section ranging from 0.2 to 7.0%.

Dacite

Dacite fragments are characterized by quartz and plagioclase phenocrysts in a fine-grained, granular, plagioclase-rich groundmass. Minor hornblende phenocrysts may also be present along with minute magnetite cubes. These fragments usually show a slight sericitic alteration, but take no stain. Visual estimation of composition indicates approximately 15% plagioclase phenocrysts, 15% quartz phenocrysts, and 70% groundmass consisting of quartz and plagioclase.

The dacite fragments comprise 20% of all the rock fragments studied. They account for 5% of all the framework grains studied with the amount of dacite fragments present in any one thin section ranging from 0.2 to 17.0%.

Andesite

Andesite fragments are characterized by hornblende phenocrysts in a groundmass of fine-grained, felty, plagioclase laths. Quartz phenocrysts are distinctly absent. The groundmass between phenocrysts varies from felty to trachytic and may contain minute crystals of magnetite and/or apatite. The hornblende phenocrysts are usually elongate, anhedral to subhedral, and may be partially or completely altered to chlorite. Visual estimation of the composition indicates approximately 20% hornblende phenocrysts and 80% groundmass consisting of plagioclase. The andesite fragments can be slightly cloudy due to sericite alteration and take no sodium-cobaltinitrate stain.

Volumetrically the andesite fragments comprise nearly 25% of all the rock fragments studied. They account for 6% of all the framework grains studied with the amount of andesite fragments present in any one thin section ranging from 0.2 to 15.0%.

Basalt

Basalt fragments are characterized by relatively coarser-grained, elongate plagioclase laths. Phenocrysts of other minerals (i.e., hornblende or augite) are hard to distinguish because the fragments are usually heavily altered to sericite. Basalt fragments commonly occur in thin section (plane polarized light) as dark gray clasts containing elongate sericite pseudomorphs after plagioclase. The basalt fragments take no stain.

Volumetrically the basalt fragments comprise 10% of all the rock fragments studied. They account for 2% of all the framework grains studied with the amount of basalt fragments present in any one thin section ranging from 0.3 to 26.3%.

Recrystallized volcanic

Recrystallized volcanic fragments are black and very fine-grained (cryptocrystalline) under plane-polarized light (Fig. 9). These fragments are very similar in appearance to tuff fragments studied in a conglomerate sample collected from the Spoon Lake structural segment. The tuff fragments in the conglomerate sample were presumably glassy (vitric) at one time since some of the fragments contain devitrified glass shards. Therefore, the recrystallized volcanic fragments may have originally been derived from a vitric tuff. In plane-polarized light the recrystallized fragments resemble mud-chips, but under crossed-nicols and high-power, crystals with individual extinction units can be observed. The recrystallized fragments are too small to compare with a stained heel to determine staining characteristics.

Volumetrically the recrystallized volcanic fragments comprise 4% of all the rock fragments studied. They account for 0.9% of all the framework grains studied with the amount of recrystallized volcanic fragments present in any one thin section ranging from 0.2 to 12.0%.

Siltstone

Siltstone rock fragments are characterized by fine-grained ($<$0.5 mm) clasts of quartz, feldspar (both orthoclase and plagioclase), hornblende, and epidote in a dark, muddy matrix. Volumetrically the siltstone fragments comprise nearly 3% of all the rock fragments studied. They account for 0.6% of all the framework grains studied with the amount of siltstone fragments present

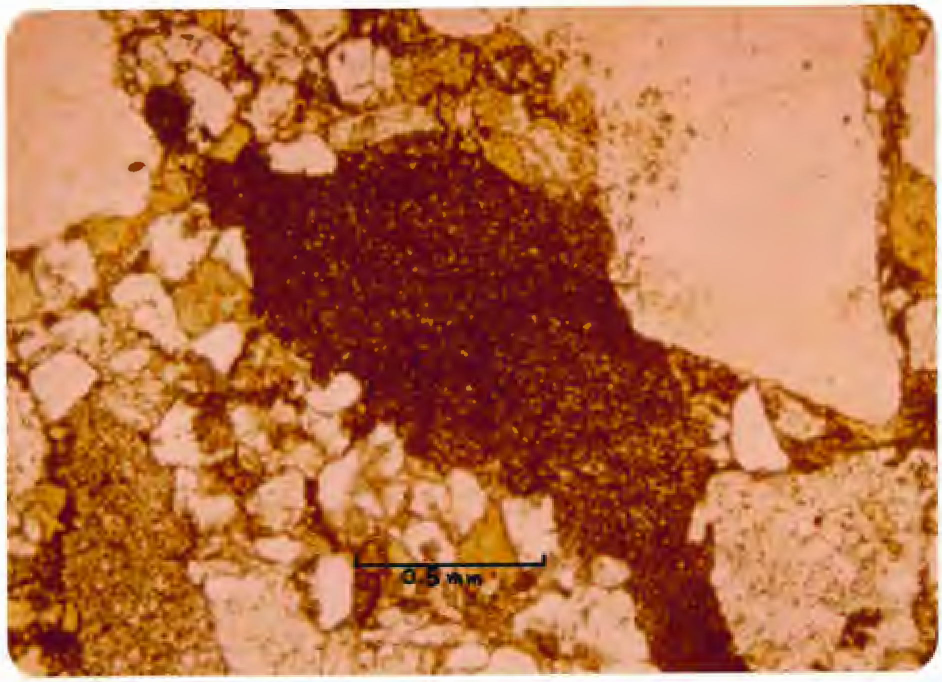


Figure 9: Photomicrograph showing recrystallized volcanic fragment (one polar). Note volcanic quartz fragment at upper right. Kekekabic Lake segment, SW1/4, NW1/4, Sec. 35, T. 65N., R. 7W.

in any one thin section ranging from 0.2 to 5.0%.

Petrographically, the hornblende andesite, hornblende trachyte-latite-trachyandesite, polycrystalline hornblende, plutonic, chert, and sericite phyllite rock fragments are described as follows:

Hornblende andesite

Hornblende andesite fragments are characterized by phenocrysts of hornblende in a plagioclase-rich groundmass. The groundmass can be granular, felty, or trachytic. Quartz phenocrysts are distinctly absent. Plagioclase laths within the felty and trachytic groundmasses vary from very fine- to coarse-grained. The hornblende phenocrysts are dominantly euhedral and commonly exhibit the pseudohexagonal amphibole cross-section (Fig. 10). In some thin sections the hornblende phenocrysts show opaque oxidized rims (Fig. 11) and may be joined by plagioclase phenocrysts. A few of the hornblende andesite fragments contain vesicles which have been infilled with secondary chlorite. The hornblende andesite fragments are usually unaltered and may be slightly pink-colored in thin section; they take no stain.

Volumetrically the hornblende andesite fragments are only significant in the Kekekabic Lake structural segment (Fig. 12) where they may comprise up to 23.0% of a particular thin section. The hornblende andesite fragments show a general decrease in abundance along the north shore of Kekekabic Lake from east to west. Noting a few exceptions, the 11 thin sections studied along strike indicate the greatest percentage of these fragments occurs at the extreme east end of Kekekabic Lake, near the portage to the Kekekabic Ponds, with the percentage decreasing to the west (near the

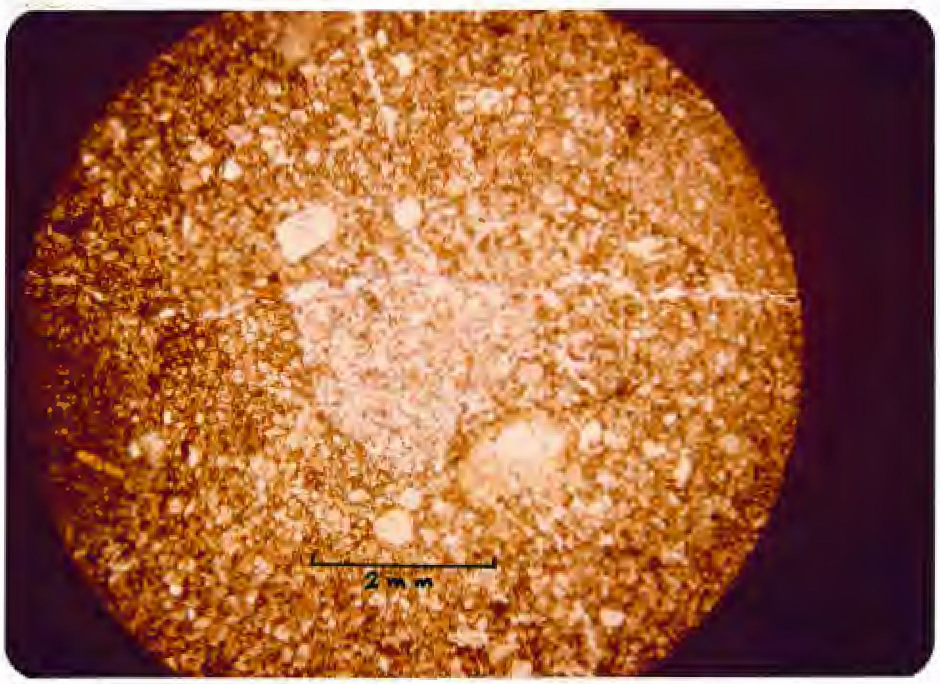


Figure 10: Photomicrograph of hornblende andesite fragment (one polar) in lithic graywacke, Kekekabic Lake segment, SE1/4, SW1/4, Sec. 29, T. 65N., R. 6W.

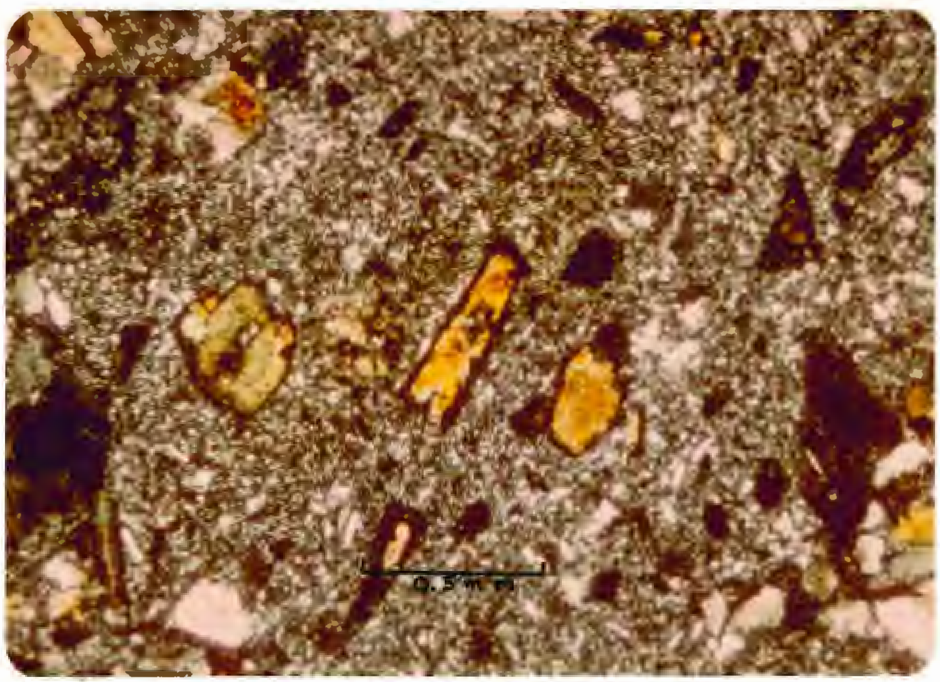


Figure 11: Photomicrograph of hornblende andesite fragment (crossed polars). Note oxidized rims on hornblende phenocrysts. Kekekabic Lake segment, SE1/4, SE1/4, Sec. 20, T. 65N., R. 6W.

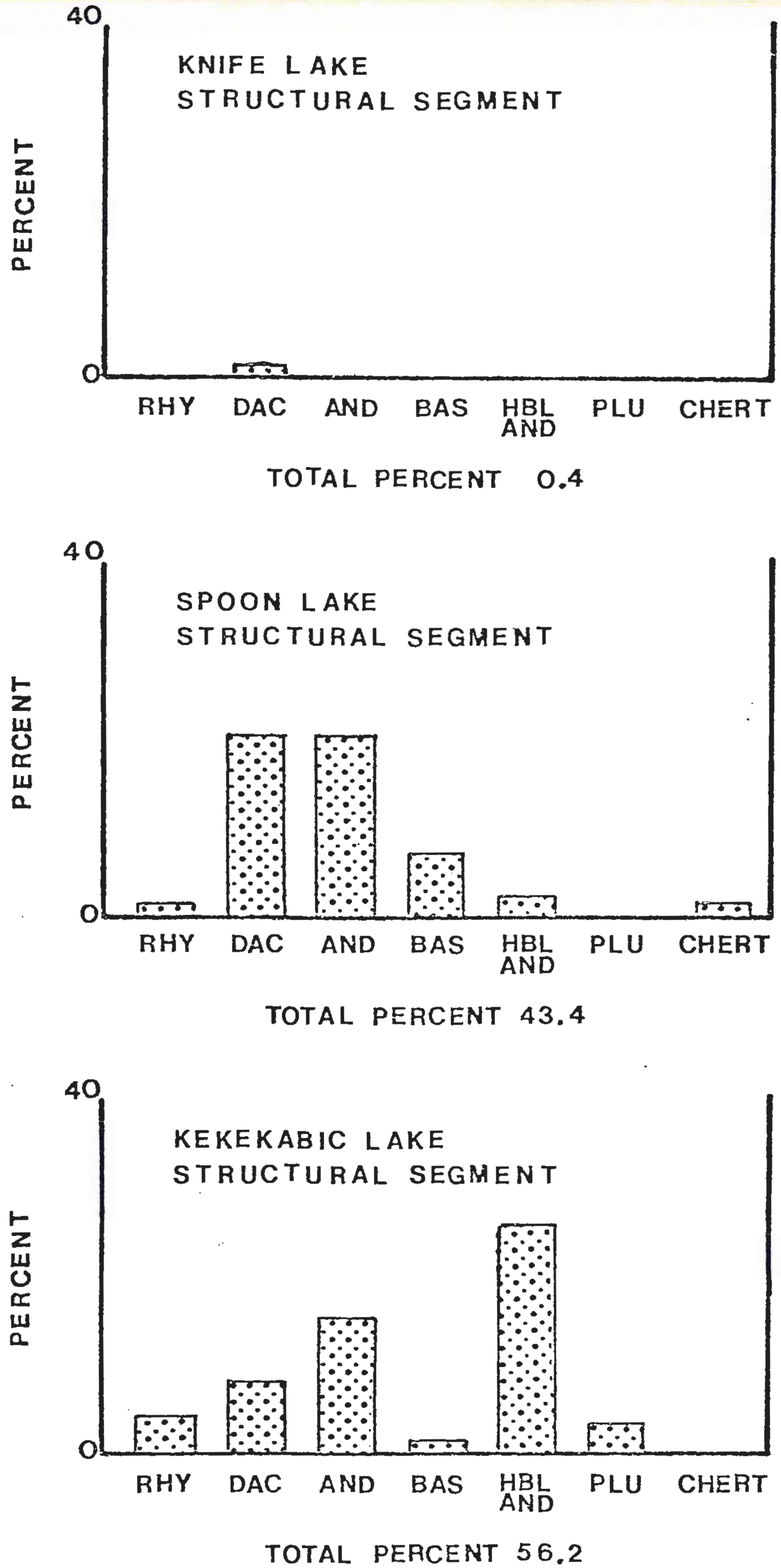


Figure 12: Summary of dominant volcanic and plutonic rock fragments studied in 11 lithic graywacke samples from the Kekekabic Lake segment, 6 lithic graywacke samples from the Spoon Lake segment, and 3 arkose samples from the Knife Lake greenstone segment. Note hornblende andesite rock fragments are only abundant in Kekekabic Lake segment as are plutonic rock fragments. Chert is only found in Spoon Lake segment. There are few rock fragments in the Knife Lake greenstone segment.

portage to Pickle Lake).

Hornblende trachyte-latite-trachyandesite

All the fragments contained in this grouping take a sodium-cobaltinitrate stain to varying degrees (Fig. 13) and thus were distinguished from andesite and hornblende andesite fragments which do not stain. The rock fragments within this group were found in only four thin sections, all of which were collected from the Kekekabic Lake segment.

		Groundmass		
	Phenocrysts	Quartz	Feldspars	Stain
Hornblende Trachyte	Hornblende	<10%	K-feldspar > 2/3 of feldspars	Deep Yellow
Hornblende Latite	Hornblende	<10%	K-feldspar = plagioclase	Med. Yellow
Hornblende Trachy-andesite	Hornblende	<10%	Plagioclase > 2/3 of feldspars	Light Yellow

Figure 13: Based on field classification of igneous rocks (after Severson, 1978, unpublished master's thesis)

In only one thin section was there a complete gradation from hornblende trachyte to latite to trachyandesite. Differentiation between the individual fragments was done in this thin section by simply comparing the staining characteristics. Within the other three thin sections no complete gradation existed. Therefore staining differences between fragments could not be readily compared. Here fragments were considered transitional and classified as hornblende trachyte to latite or latite to trachyandesite.

All of the fragments in this group are characterized by phenocrysts of hornblende in a feldspathic groundmass. Quartz phenocrysts are distinctly absent. The groundmass varies from granular to trachytic between phenocrysts and may include minor apatite, pyrite, and epidote. The hornblende phenocrysts usually are euhedral and commonly exhibit the pseudohexagonal amphibole cross-section. The fragments within this group are relatively unaltered.

Of the four thin sections point counted, hornblende trachyte fragments comprise 4% of all the framework grains; hornblende latite 0.6%; and hornblende trachyandesite 1.3%.

Polycrystalline hornblende

Polycrystalline hornblende rock fragments are found only in the Kekekabic Lake structural segment. They are composite fragments that have more than one extinction unit and are composed of anhedral to subhedral hornblende crystals (Fig. 14). The fragments are generally fresh but can be partially or completely pseudomorphed to muscovite.

The polycrystalline hornblende fragments do not resemble hornblende phenocrysts seen in dacite, andesite, and hornblende andesite rock fragments. Therefore, they are apparently not derived from intrusive and extrusive igneous rocks, but may be tuffaceous crystal clots which were blown out before consolidation.

Volumetrically the polycrystalline hornblende rock fragments may comprise up to 7.6% of a particular thin section.

Plutonic rock fragments

Plutonic rock fragments are characterized by quartz-feldspar aggregates. The quartz is generally common undulose quartz but

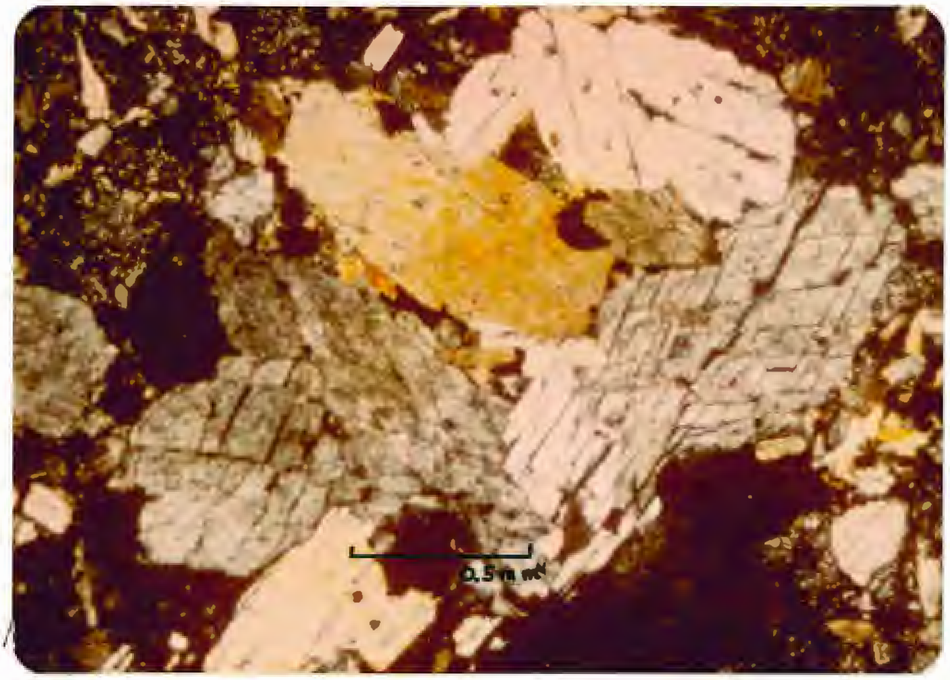


Figure 14: Photomicrograph showing polycrystalline hornblende fragment (crossed polars). Kekekabic Lake segment, SW1/4, SE1/4, Sec. 29, T. 65N., R. 6W.

can also be polycrystalline. The feldspar is usually partially altered to sericite and difficult to identify; but is commonly albite. Unlike the volcanic rock fragments, the plutonic fragments are non-porphyritic.

All of the plutonic fragments examined in one thin section from the south shore of Kekekabic Lake resemble Saganaga Tonalite. These fragments have large polycrystalline quartz "eyes" and altered plagioclase laths.

The plutonic fragments are most abundant in the Kekekabic Lake structural segment, particularly near the east end of Kekekabic Lake.

Volumetrically, the plutonic fragments may comprise up to 3.6% of a particular thin section.

Chert

Chert fragments are most abundant in the Spoon Lake structural segment where they may comprise up to 3.3% of a particular thin section. Some of the chert fragments studied may actually be rhyolite and vice-versa. Chert fragments were not found in the Kekekabic Lake structural segment (Fig. 12).

Sericite Phyllite

A sericite phyllite rock fragment was found in one sample collected from the Kekekabic Lake structural segment. The fragment contained long stringers of sericite with the sericite crystals optically aligned to give the appearance of a foliation within the fragment. The sericite phyllite fragment comprised 13.0% of the thin section studied.

Operational definitions, Igneous rocks

Igneous rocks within the present area of study, including dikes and intrusives, were classified according to Figure 15. In addition, several igneous terms which will be used in this paper are defined below. They include:

Diabase:	A relatively fine-grained gabbro which has an ophitic texture and random plagioclase laths.
Lamprophyre:	A dark-colored, porphyritic igneous rock characterized by panidiomorphic texture, a high percentage of mafic minerals (esp. biotite, hornblende, and pyroxene) which form the phenocrysts, and a fine-grained groundmass with the same mafic minerals in addition to feldspars (Gary and others, 1974).
Tuff:	Lithified volcanic ash 0.25 to 4.0 mm in diameter. The variety of tuff found in the present study area is crystal tuff which consists predominantly of crystals of plagioclase and fragments of plagioclase crystals.
Agglomerate:	1) a pyroclastic rock that consists of angular volcanic fragments and/or 2) accidental or non-volcanic fragments in a volcanic matrix. The fragments in both cases are greater than 2.0 mm in diameter.

Petrology of the Knife Lake Greenstone Segment

The Knife Lake greenstone segment comprises approximately 0.5 square miles in the northwest corner of the present study area (Plate 1). It is a triangular-shaped area with the base of the triangle located at Bonnie Lake and the apex near an outcrop of Ely greenstone to the northeast. For the purposes of this paper

Ratio of Feldspars	Alakali-Feldspar Predominant (> 2/3 of fsp)		Two Feldspars about equal		Plagioclase Predominant (> 2/3 of fsp)		Only Plagioclase (> 95% of fsp)			
							Sodic An 1-49		Calcic An 50-100	
Mafics	Biotite and/or Hornblende increasing		Muscovite						Pyroxene, Olivine	
Quartz	>10% QZ	< 10% QZ	>10% QZ	<10% QZ	>10% QZ	< 10% QZ	> 10% QZ	<10% QZ	QZ	NO QZ
Texture: Phaneritic	GRANITE	Syenite	ADAMELLITE (Quartz Monzonite)	Monzonite	GRANODIORITE	Syenodiorite	TONALITE (Quartz Diorite)	DIORITE	Quartz Gabbro	GABBRO

Figure 15: Classification used in this study for igneous rocks (after Green, 1970)

the Knife Lake greenstone segment is truncated to the north by the south arm of Knife Lake and to the south by a major longitudinal fault (Gruner, 1941). The rocks contained in this segment trend east-northeast and dip steeply to the southeast. They are apparently not folded since no reversals of dips were observed. The stratigraphic thickness of this segment was not measured in the field but is estimated to be 250 feet (Plate 2). A total of six thin sections from the Knife Lake greenstone segment were used for petrographic study.

<u>Description of rock types</u>

Arkose

Arkose is the dominant lithology in the Knife Lake greenstone segment. Megascopically the rocks are white on the weathered surface and dark gray to gray on the fresh fracture. They are medium-grained (avg. clast size 0.5 to 1.0 mm) and may exhibit coarse (up to 2.0 mm) clasts of quartz and feldspar in a finer-grained matrix. Arkose beds range from 0.5 to 10 cm in thickness with the average thickness being 8 cm. Only a few beds are graded. Interbedded with the arkoses are laminae (0.5 cm thick) and beds (3.5 cm thick) of black slate.

A total of three thin sections were used for petrographic study of the arkoses. Table 1 is a summary of the modal analyses.

The abundance of matrix and the predominance of feldspar over volcanic rock fragments indicates the arkoses should be correctly called feldspathic graywackes (Fig. 8). However, according to Pettijohn and others (1972), a graywacke has a "fine-

TABLE 1--ARKOSE MODES FROM
KNIFE LAKE GREENSTONE SEGMENT

*Modal Analyses of Arkose,
Knife Lake Greenstone Segment

	1	2	3
Undulose common qtz.	9.0	10.8	7.6
Volcanic quartz	—	0.8	—
Plagioclase	36.3	47.1	37.6
Rock Fragments:			
Rhyolite	—	—	—
Dacite	—	0.2	—
Andesite	—	—	—
Basalt	—	—	—
Mud chips	—	10.3	—
Chlorite	2.5	—	—
! Sericite	1.3	0.2	0.5
Carbonate	6.5	—	0.8
Matrix	22.0	28.8	47.0
!! Opaques	6.8	0.8	3.6
Others	15.1[a]	0.8	2.0

* 600 points per thin section along traverses normal to bedding
! Found in matrix, also as alteration of plagioclase
!! Predominantly magnetite, some ilmenite
(a) Mostly fractures infilled by quartz

grained matrix consisting of an intimate intergrowth of chlorite, sericite, and minute silt-sized particles of quartz and feldspar." The matrix within the arkose samples is a fine-grained ($<$ 0.25 mm), granular, interlocking mixture of predominantly quartz and minor plagioclase. A feldspathic sandstone having a matrix of interlocking grains was referred to by Tieje (1921) as an arkositite. In this paper it is considered to be an arkose.

In thin section (Fig. 16), the arkose samples are angular to subangular, and moderately sorted. Quartz and plagioclase are the dominant clasts in the arkose samples with minor rock fragments (mud chips) found in one section. The quartz clasts all appear to be common undulose quartz but some have pyramidal terminations and may have originally been volcanic quartz. Plagioclase clasts are usually elongate, polysynthetically twinned, zoned, and partially or completely altered to sericite. Some of the twinned plagioclase clasts are deformed. Minor carbonate, opaques, and sericite are found in the matrix. Magnetite bands (1 to 4 mm in thickness) composed of euhedral magnetite cubes were found in two samples studied. Some of the magnetite may actually be ilmenite since leucoxene is also present in the bands.

Ely Greenstone

Ely Greenstone occurs at the apex of the triangle outlined by the Knife Lake greenstone segment. It was mapped by Gruner (1941) and reexamined during the present study. This exposure should not be regarded as true Ely Greenstone since it is impossible to correlate this outcrop with the type section of Ely Greenstone in

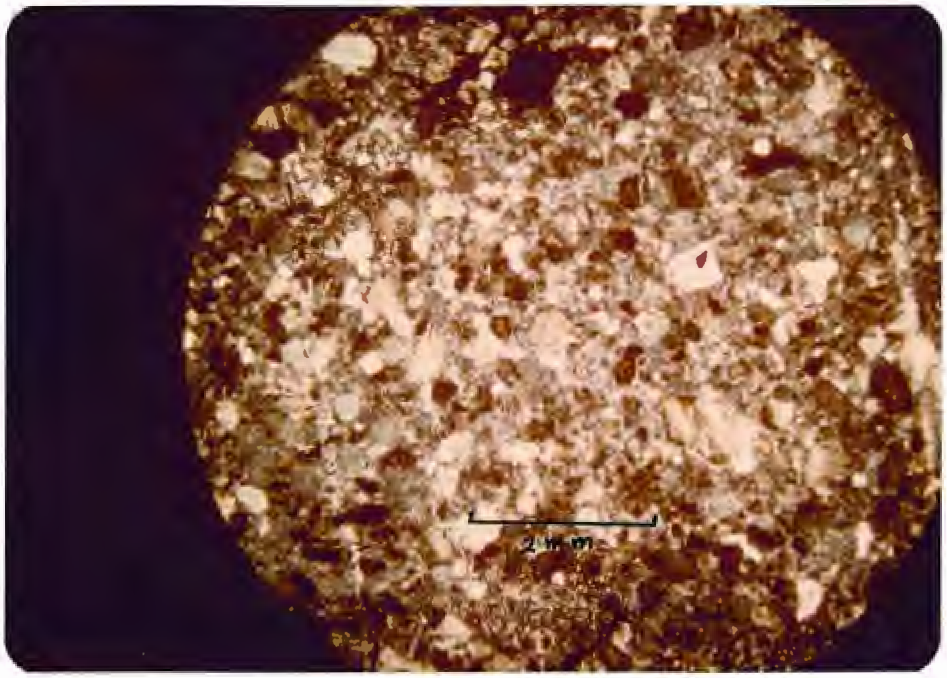


Figure 16: Photomicrograph of arkose (crossed polars). NW1/4, NW1/4, Sec. 26, T. 65N., R. 7W.

Ely, Minnesota. In this paper the outcrop is considered to be a metabasalt (greenstone) which is dioritic in composition and may be similar to the greenstones at Ely. The contact relationship between the greenstone and the adjacent arkoses could not be determined in the field.

Megascopically the outcrop is brownish orange on the weathered surface and dark green on the fresh fracture. The weathered surface has a pitted appearance, probably due to the weathering out of mafic minerals (pyroxenes), and exhibits elongate (1 mm to 1 cm in length) needles of plagioclase. Minor gold-colored elongate blades were also seen in hand specimen and were thought to be an alteration product of mafic minerals.

Only one thin section was used for petrographic study; Table 2 shows the modal analysis. In thin section, the greenstone is fine-grained (avg. crystal size <1 mm), holocrystalline, hypidiomorphic to panidiomorphic, contains a felty groundmass, and possibly some graphic intergrowths. The sample is generally fresh with only the plagioclase crystals being partially altered to sericite. However, the presence of serpentine and alunite (?) indicates the greenstone may have undergone hydrothermal alteration. Fractures seen in thin section are lined by alunite and infilled by quartz and carbonate. Plagioclase determinations using the Michel-Levy method were not possible due to the altered nature of the plagioclases.

Diorite

A small outcrop of diorite occurs along the eastern shore of

TABLE 2--MODES FROM IGNEOUS ROCKS IN KNIFE LAKE GREENSTONE SEGMENT

Modal Analyses of Igneous Rocks, Knife Lake Greenstone Segment		
	Ely Greenstone	Diorite
Undulose common qtz.	8.0	2.8
Plagioclase	30.6	50.0
Hornblende	15.3	11.3
Augite	0.2	12.5
Pigeonite	—	5.0
Chlorite	2.5	6.8
Epidote	4.0	—
Serpentine	6.6	—
Carbonate	2.6	3.5
Opaques	0.5	8.6
Hydrothermal alteration product (Alunite)	24.0	—
Others	5.5	3.5

Bonnie Lake (Plate 1). The contact relationship between the diorite and the adjacent arkoses was obscured by thick vegetation.

Megascopically, the diorite outcrop is buff to light orange on the weathered surface, dark green on the fresh fracture, and is fine- to medium-grained (avg. crystal size 0.5 to 1.0 mm).

One thin section was studied from the outcrop; Table 2 shows the model analysis. Microscopically the sample is holocrystalline and hypidiomorphic. It has a felty plagioclase groundmass and dikytaxitic cavities filled with carbonate and chlorite. Reaction rims of hornblende around pyroxene are also present. Magnetite cubes, some poikilitic, occur throughout the slide. The sample is relatively fresh with the plagioclases being partially altered to sericite. The composition of one plagioclase crystal, using the Michel-Levy method, was found to be An_{54}.

Petrology of the Spoon Lake Segment

The Spoon Lake segment comprises approximately 2.5 square miles in the present area of study (Plate 1). It is a relatively narrow, rectangular-shaped segment that incorporates Spoon and Sema Lakes within its limits. The Spoon Lake segment is bounded to the north and south by major longitudinal faults (Gruner, 1941). This segment is in fault contact with the Knife Lake greenstone segment to the north and the Kekekabic Lake segment to the south. The rocks within the Spoon Lake segment strike predominantly north-east and dip steeply to the southeast. The rocks are folded, with reversals of dipping and topping directions indicating that a major syncline is present near the northern boundary of the segment (Plate 2). The syncline plunges 35^{o} to the southwest. The stratigraphic thickness of the segment was not measured in the field but is estimated to be at least 800 feet (Plate 2). A total of twenty-one thin sections from the Spoon Lake segment were used for petrographic study.

Description of rock types

Graywacke is the dominant lithology in the Spoon Lake segment. The graywackes studied are equally divided between the lithic and feldspathic subtypes. No generalization can be made as to where the lithic or feldspathic graywackes occur since both subtypes seem to be randomly distributed throughout the segment.

Megascopically the lithic and feldspathic graywackes are identical. Both are white to light orange on the weathered surface; green on the fresh fracture, and fine- to medium-grained (avg. clast size $<$0.5 to 1.0 mm). Graywacke beds range from 1 to 15 cm in thickness with the average thickness being 7 cm. Some of the beds pinch out over a short distance while others thin and thicken over their exposed lengths. Nearly one-third of the graywacke beds are graded with the predominant grading being from medium-grained, at the base of the bed, to fine-grained at the top. A large mudchip (Fig. 17) was found in one graded graywacke sequence while flame structures are present in others. Slates are interbedded with the graywackes and range from 1 to 9 cm in thickness. The slates are light orange on the weathered surface and green on the fresh fracture. Interbedded within the green slates in some outcrops are bands (2 to 6 cm thick) of ferruginous

Figure 17: Photograph of large mudchip (above), NW1/4, SE1/4, Sec. 24, T. 65N., R. 7W; and flame structure (below), SW1/4, SE1/4, Sec. 19, T. 65N., R. 6W.

slate. These bands are reddish purple to black and rhythmically alternate with the green slate beds.

Lithic graywackes

Lithic graywackes were studied in six thin sections. Table 3 shows the modal analyses. In thin section, the lithic graywackes are angular to subrounded and are generally poorly sorted although two samples were moderately sorted. Rock fragments within the lithic graywackes are predominantly dacite and andesite. Quartz clasts are generally common undulose quartz with minor amounts of volcanic and polycrystalline quartz also present. Plagioclase clasts are partially altered to sericite with some complete pseudomorphs to sericite seen in one thin section. Hornblende comprises a minor portion of the lithic graywackes. Matrix within the lithic graywackes is composed of minute hornblende, quartz, and plagioclase clasts along with chlorite and sericite. Bedding, defined by the parallel alignment of elongate rock fragments, was observed in one thin section. Graded bedding was not seen in any of the thin sections, but was observed in outcrop as previously mentioned.

Feldspathic graywackes

Feldspathic graywackes were studied in five thin sections. Table 4 shows the modal analyses. The feldspathic graywackes are angular and moderately sorted in thin section. Rock fragments in the feldspathic graywackes are generally dacite and andesite. Plagioclase clasts are equant to elongate, polysynthetically twinned, and partially or completely altered to sericite (Fig. 18). Common quartz and hornblende comprise the remainder of the feld-

TABLE 3--LITHIC GRAYWACKE MODES FROM SPOON LAKE SEGMENT

*Modal Analyses of Lithic Graywackes, Spoon Lake Segment

	1	2	3	4	5	6
Undulose common qtz.	6.3	5.2	5.0	6.8	11.1	5.3
Volcanic quartz	0.3	—	—	0.2	1.0	1.3
Polycrystalline quartz	—	0.4	—	—	—	—
Plagioclase	14.5	14.8	18.5	8.6	20.5	9.6
! K-feldspar	—	0.8	—	—	—	—
Rock Fragments:						
!! Rhyolite	—	2.6	0.6	0.2	—	3.6
Dacite	12.8	4.4	14.6	5.1	10.5	16.8
Andesite	9.6	8.0	10.1	5.8	11.8	15.1
Basalt	3.6	0.8	13.2	1.1	26.3	13.0
Hbl Andesite		4.6		0.8		
Recrystallized vol.	7.5	—	0.4	0.2	—	11.5
Siltstone	3.5	0.4	—	0.2	4.5	1.3
Chert	0.6	0.6	0.1	—	0.8	3.3
Total rock fragments:	37.6	21.4	39.0	13.4	53.9	64.6
Hornblende	2.5	7.8	—	2.1	—	0.8
** Chlorite	2.0	7.6	5.6	1.0	1.0	1.3
Epidote	—	0.6	—	—	—	—
Sericite	—	—	0.2	—	—	—
Muscovite	—	—	0.2	—	—	—
Carbonate	7.0	1.8	7.3	0.2	1.0	9.8
Matrix	27.2	33.2	19.6	60.1	11.0	0.3
Opaques	0.8	1.8	0.8	3.3	—	0.3
Others	1.2	4.6	2.6	4.0	0.3	6.1 (a)

* 600 points per thin section along traverses normal to bedding
** Occurs as spots in matrix
! K-feldspar percentages aided by staining
!! May include minor chert
(a) Mostly fractures infilled with quartz

TABLE 4--MODES OF FELDSPATHIC GRAYWACKES
IN SPOON LAKE SEGMENT

*Modal Analyses of Feldspathic Graywackes, Spoon Lake Segment

	1	2(a)	3	4	5
Undulose common qtz.	14.2	2.2	8.5	1.8	4.9
Volcanic quartz	0.8	—	—	—	0.2
Polycrystalline quartz	—	—	1.1	1.0	0.4
Plagioclase	35.5	4.8	24.3	47.7	24.9
! K-feldspar	—	—	0.2	—	0.5
Rock Fragments:					
!! Rhyolite			0.8	0.3	0.7
Dacite	14.8	—	5.8	2.6	2.4
Andesite	8.5	—	4.8	11.1	3.4
Basalt	0.3	—	0.6	—	—
Hbl Andesite	—	—	1.6	0.8	2.0
Recrystallized vol.	—	—		9.3	
Siltstone	—	—	—		—
Chert	0.3	—	0.5	1.1	0.5
Total rock fragments:	23.9	0.0	14.1	25.2	9.0
Hornblende	—	3.4	12.2	14.4	3.2
** Chlorite	—	1.1	4.3	2.4	2.4
Epidote	—	2.8	—	1.4	3.7
Sericite	1.0	—	—	—	—
Muscovite	—	—	—	—	—
Carbonate	0.5	4.3	3.0	0.3	—
Matrix	20.2	65.7	27.6	—	48.6
Opaques	1.0	—	0.8	0.7	0.6
Others	2.8	15.4(b)	3.5	4.8	1.3

* 600 points per thin section along traverses normal to bedding
** Occurs as spots in matrix
! K-feldspar percentages aided by staining
!! May include minor chert
(a) Only 350 points
(b) Fractures filled with quartz and carbonate

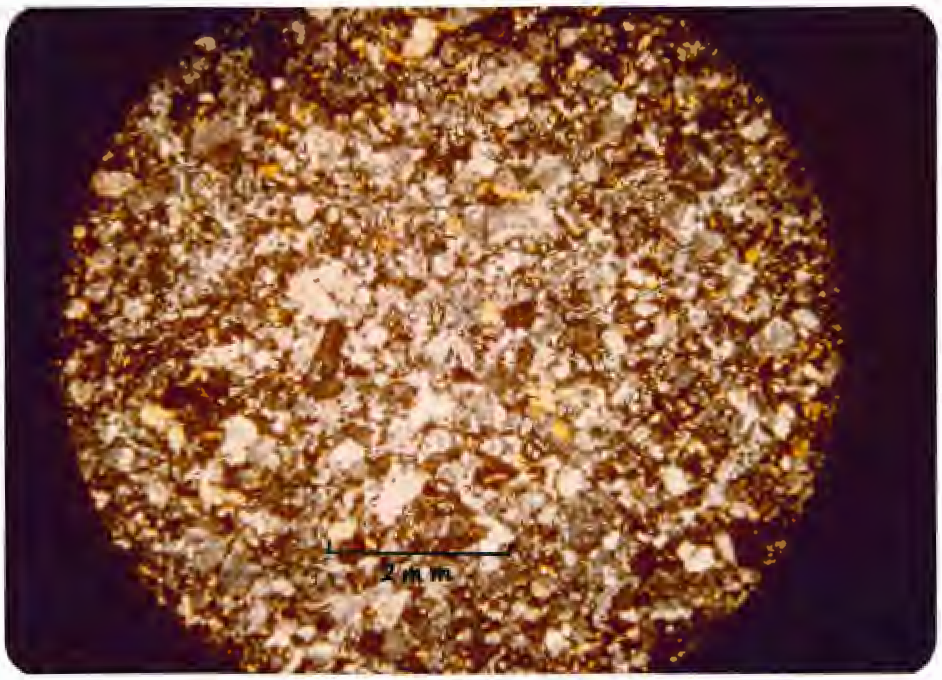


Figure 18: Photomicrograph of feldspathic gray-
wacke (crossed polars). NE1/4, NE1/4, Sec. 26,
T. 65N., R. 7W.

spathic graywackes with minor amounts of volcanic quartz, polycrystalline quartz, and orthoclase also present. Crude bedding was seen in all the thin sections and was defined by the parallel alignment of plagioclases and elongate rock fragments. Matrix within the feldspathic graywackes is identical to the matrix in the lithic graywackes and is composed of quartz, plagioclase, hornblende, chlorite, and also epidote.

Conglomerate

Four conglomerate beds are exposed in one outcrop which is located in the NE1/4, NW1/4, SE1/4, of Sec. 24, T. 65N., R. 7W. (Plate 1). The conglomerate beds range from 2 to 154 cm in thickness and have an average thickness of approximately 40 cm. Fine-grained (avg. clast size $<$0.5 mm) graywacke beds, 10.5 to 116 cm thick, are interbedded between the conglomerate beds. The conglomerate beds are part of a graywacke-slate-conglomerate sequence which is described in more detail on page 134. They make up 4% of this sequence with previously described graywackes and interbedded green slates comprising the remaining 96%. Within this one outcrop, bedding and topping directions indicate the conglomerate is at the base of the graywacke-slate-conglomerate sequence. However, since this outcrop cannot be correlated with other rock exposures, it is not known at the present time whether the conglomerate is a basal conglomerate or simply interstratified within the graywackes and slates.

Megascopically the conglomerate beds are very similar to the graywackes, being light orange to white on the weathered surface with a green matrix between the clasts on the fresh fracture (Fig. 19). Clasts within the conglomerate beds are rounded and approximately 10 mm in diameter but can range up to 5 cm in diameter. The clasts are tan to buff on the weathered surface and dark green to black on the fresh fracture. A pebble count was not done in the field because the clasts are too fine-grained (microscopic) to identify (i.e. whether they are dacite, andesite, etc.).

The conglomerate was studied in only one thin section. It is composed of volcanic rock fragments and matrix (Fig. 20). Rhyolite comprises 4% of the thin section, dacite 14%, andesite 10%, basalt 6%, recrystallized volcanic fragments 2%, intermediate tuff 36%, and matrix 28%. The matrix is composed of angular hornblende, quartz, and feldspar clasts, and smaller ($<$ 0.06 mm in diameter) rock fragments. Minor chert and carbonate make up the remainder of the matrix.

Intermediate (latite to trachyandesite) tuff fragments (Fig. 20) appear brown in thin section (one polar), are cryptocrystalline, contain minute devitrified glass shards, and have carbonate, magnetite, and some ilmenite as alteration and accessory minerals, respectively.

Mafic tuff

Mafic (basalt or andesite) tuff beds are found in one outcrop which is located in the NE1/4, SW1/4, NW1/4, of Sec. 25, T. 65N., R. 7W. (Plate 1). In outcrop, the tuff beds look very similar to graded graywackes. They are tan on the weathered surface, green on the fresh fracture, and fine- to medium-grained (avg. clast

Figure 19: Photograph showing conglomerate beds. NW1/4, SE1/4, Sec. 24, T. 65N., R. 7W.

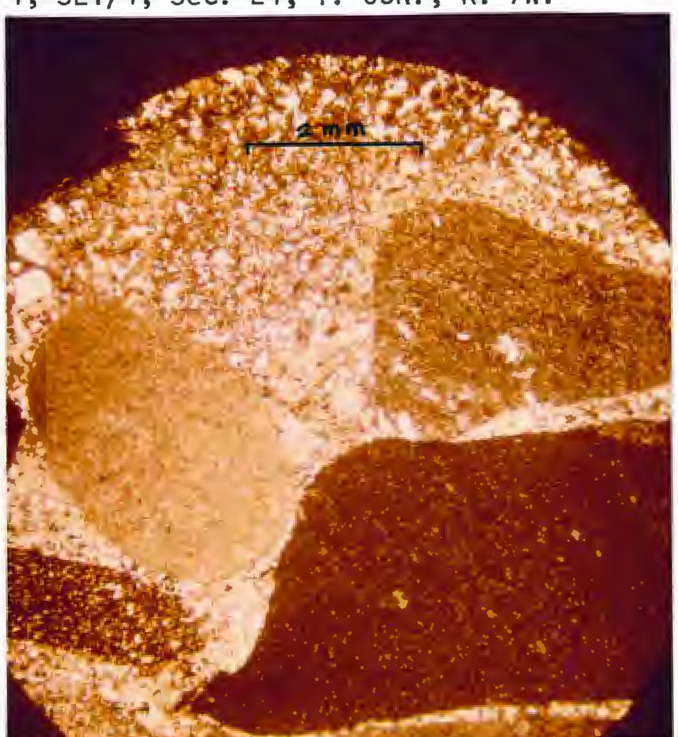


Figure 20: Photomicrograph of conglomerate sample (one polar) showing intermediate tuff fragment at lower right, andesite fragment at left, and basalt fragment at upper right. NW1/4, SE1/4, Sec. 24, T. 65N., R. 7W.

size $<$ 0.5 to 1.0 mm). A total of 25 tuff beds are contained in this one outcrop and range from 0.5 to 300 cm in thickness with the average thickness being 17.2 cm. Green slate beds, 0.5 to 90 cm in thickness, are interbedded with the tuffs and have an average thickness of 15 cm. Of the tuff beds studied in this one outcrop (a detailed description is given on page 134), 76% are graded. The predominant grading is from medium- to fine-grained. Bedding and topping directions indicate the tuff beds occur in the south limb of the syncline shown in Plate 2 and are apparently inter-stratified within the graywackes and slates.

Tuff was not used in the field to describe the units in this one outcrop. The term was only used after petrographic study had revealed two graded samples from the outcrop to be crystal tuffs rather than graywackes. It was then assumed, tacitly, that most of the fine- to medium-grained beds were tuff. The presence of slates and a few finely-laminated slates between tuff beds would seem to indicate the tuff was deposited directly into water. The lack of "complete" or partial (B-C-D) Bouma sequences between tuff beds indicates turbidity currents were not responsible for tuff deposition.

In the two thin sections studied, the mafic tuff has an average mode of 74% plagioclase crystals and 20% matrix. Minor amounts of hornblende, carbonate, rock fragments, and quartz-veins comprise the remainder. The plagioclase crystals are subhedral to euhedral and well sorted. Only a few of the crystals are broken. Bedding is seen in one thin section and is defined by a difference in crystal sizes (Fig. 21). Plagioclase crystals are polysynthet-

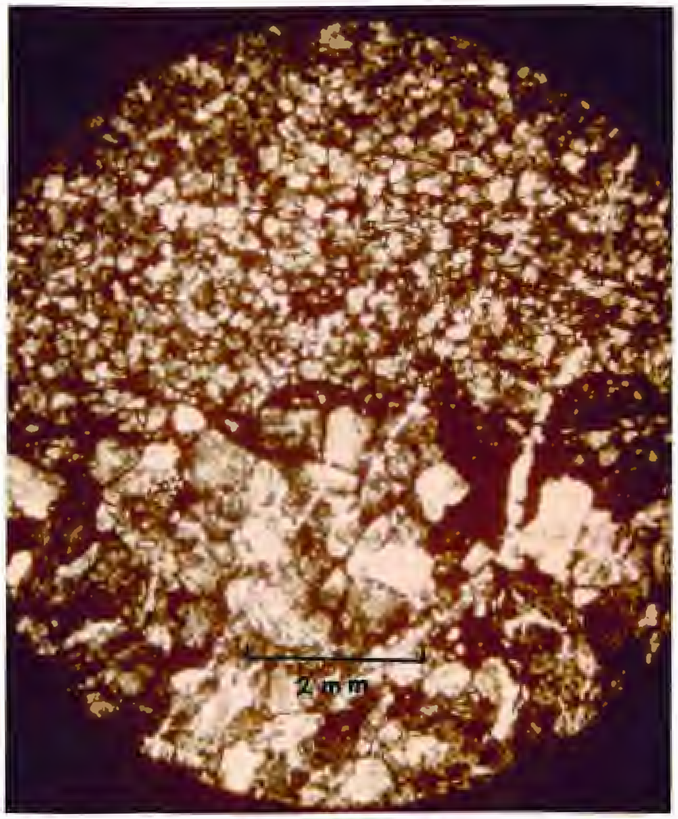


Figure 21: Photomicrograph of an apparent water-laid, mafic crystal tuff (crossed polars). Note bedded appearance. SW1/4, NW1/4, Sec. 25, T. 65N., R. 7W.

ically twinned, deformed, zoned (calcic cores), and heavily altered to sausserite and/or sericite. Matrix within the two thin sections is a mixture of carbonate, chlorite, and epidote. In addition, a very fine-grained ($<$ 0.05 mm) interlocking matrix of quartz (chert) and possibly minor plagioclase was seen in one thin section.

Fault breccia

Fault breccia was studied in four samples. These samples were all collected from the southern margin of the Spoon Lake segment along the major longitudinal fault that separates the Spoon Lake and Kekekabic Lake segments (Plate 1). The four samples were randomly collected but are approximately equally spaced from west to east along the fault. Fault breccia was not recognized in the field as a distinct unit. The samples collected were badly weathered and simply called graywackes. Fault breccia was only used after petrographic study revealed the four samples to be highly fractured. The fault breccia apparently comprises a zone, approximately 500 feet wide, along the longitudinal fault.

In thin section, the fault breccia is composed of predominantly plagioclase clasts (avg. clast size 0.5 to 1.0 mm) set in a black, chlorite-rich, sheared matrix (Fig. 22). The plagioclase clasts show complex polysynthetic twinning and are commonly deformed. Also conspicuous in the fault breccia are angular rock fragments (Fig. 23). The plagioclase clasts and the rock fragments both resemble porphyritic syenodiorite samples collected from the Kekekabic Lake segment (Fig. 24). The porphyritic syenodiorite is a

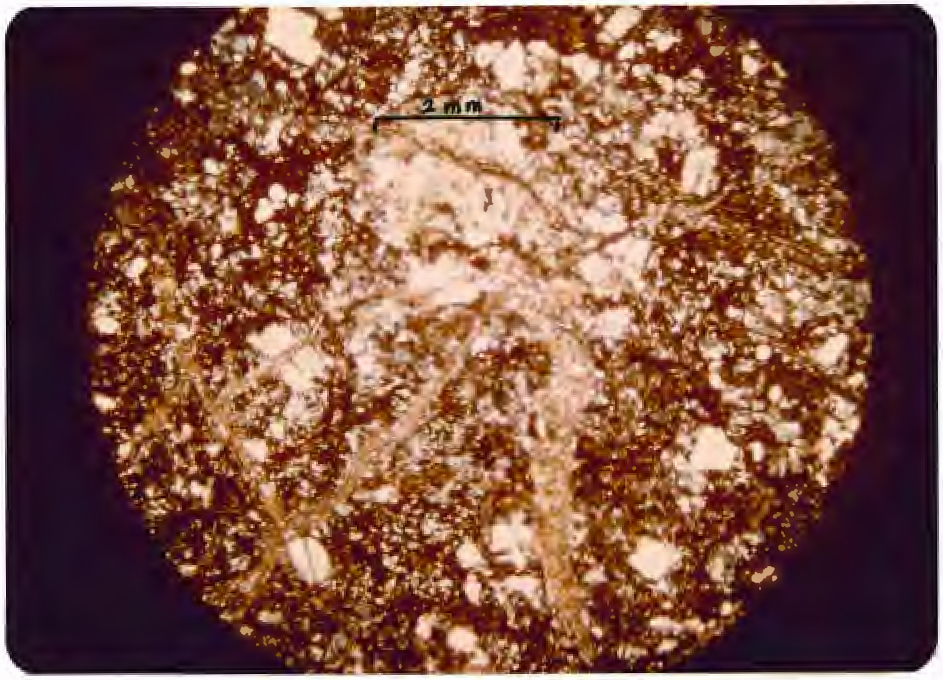


Figure 22: Photomicrograph of fault breccia exposed along longitudinal fault between Spoon and Kekekabic Lake segments (crossed polars).

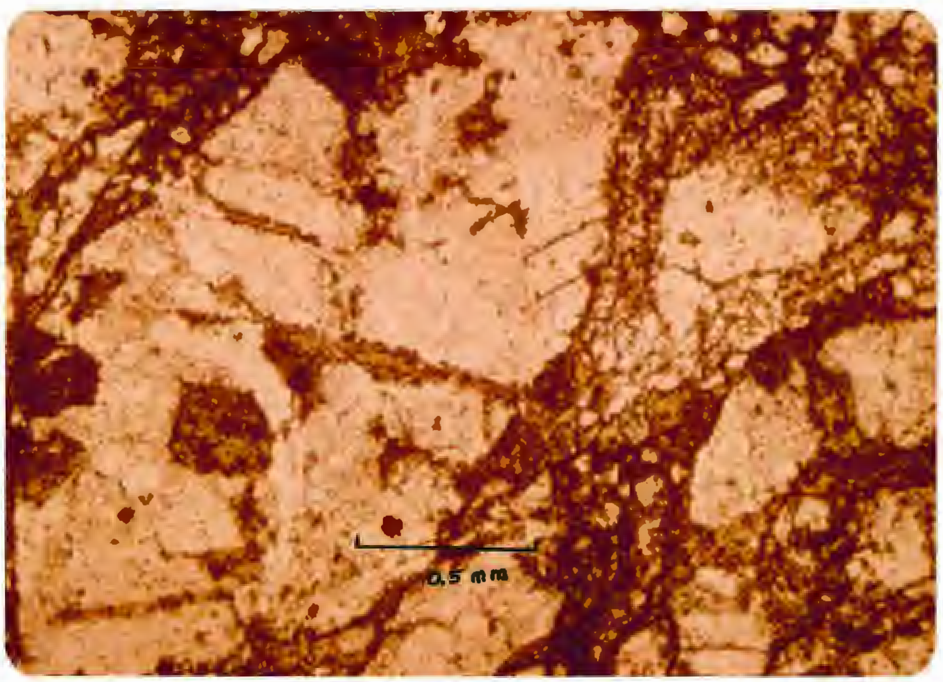


Figure 23: Photomicrograph of brecciated rock fragment within fault breccia (one polar).

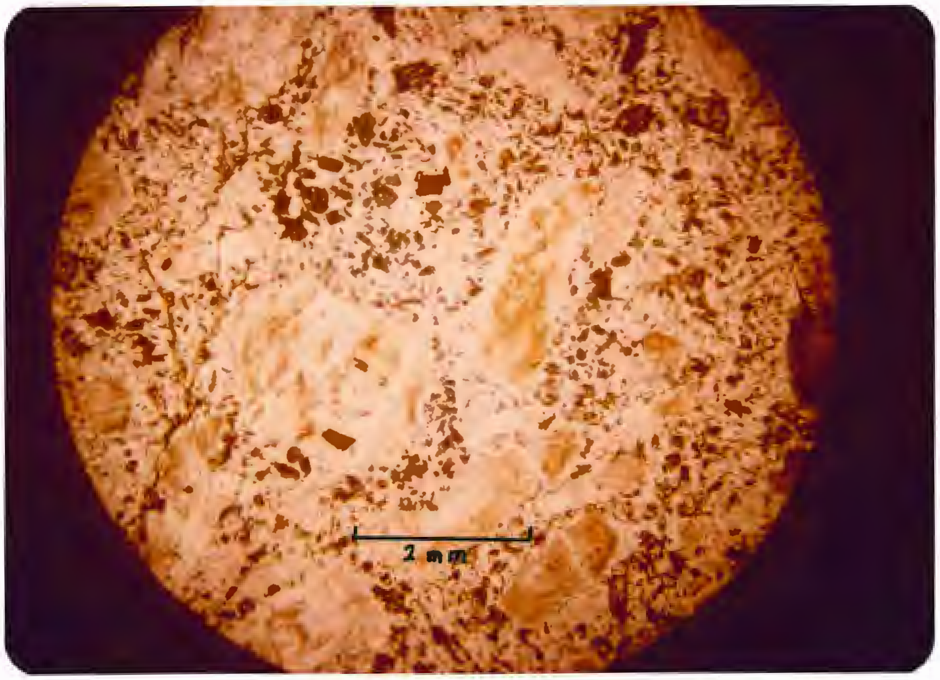


Figure 24: Photomicrograph of porphyritic syenodiorite (one polar). Kekekabic Lake segment, NE1/4, NE1/4, Sec. 36, T. 65N., R. 7W.

less common facies of the Kekekabic stock which is considered to be syntectonic or late-syntectonic with regional folding (Stark, 1927). Emplacement of the syenodiorite (either during or after folding) was apparently followed by longitudinal faulting which resulted in brecciation of the porphyritic syenodiorite.

Arkose

One arkose sample was collected from the north shore of Pickle Lake near the portage to Spoon Lake (Plate 1).

Microscopically the arkose consists of 22% plagioclase, 12% undulose common quartz, 3% sericite, and 48% matrix. Minor sericite, carbonate, dacite rock fragments, and opaques comprise the remainder of the thin section. The arkose sample is texturally and compositionally similar to the arkose samples of the Knife Lake greenstone segment.

The arkose sample of the Spoon Lake segment may be simply interstratified within graywackes and slates or it may represent the contact between Gruner's (1941) massive arkoses and overlying graywackes and slates of the Amoeba Lake member of the Knife Lake Group. If the latter, as herein assumed, then the Spoon Lake segment has moved down relative to the Knife Lake greenstone segment (Plate 2). The downward displacement would be a minimum of 800 to 1000 feet. Gruner's (1941) cross-section across the same area also shows the Spoon Lake segment to have moved downward relative to the Knife Lake greenstone segment.

Diabase

One diabase dike was found in the Spoon Lake segment. It cuts across a small point of land that is located in the NW1/4, NE1/4, SE1/4, of Sec. 26, T. 65N., R. 7W. (Plate 1). The dike was originally mapped by Gruner (1941) and reexamined during the present study. It is approximately 500 feet long and 5 to 10 feet wide. Megascopically the dike is light green on the weathered surface, purple on the fresh fracture, and exhibits conspicuous plagioclase laths up to 1 mm in length.

In thin section, the dike is composed of 63% plagioclase (An_{68}), 28% augite (minor pigeonite), 5% olivine, and 4% opaques (mainly magnetite). The one thin section studied is fine-grained (avg. crystal size 0.75 mm), holocrystalline, hypidiomorphic, felty, and ophitic. In addition, the olivine and magnetite crystals are poikilitic with plagioclase. Olivine crystals are altered to iddingsite and rimmed by magnetite. Plagioclase laths have a slight sausserite alteration.

Petrology of the Kekekabic Lake Segment

The Kekekabic Lake segment comprises approximately 3.0 square miles in the present area of study and is by far the most interesting of the three segments studied. In map view (Plate 1), the segment appears as an elongate rectangle that is bordered to the north by a major longitudinal fault and to the south by Kekekabic Lake. The Kekekabic Lake segment is in fault contact with the Spoon Lake segment to the north. Rocks within the Kekekabic Lake segment trend northeast and dip predominantly to the southeast with steep dips. Reverals of dip and topping directions indicate the rocks are folded into a syncline which encompasses the entire segment and plunges 30° to the southwest (Plate 2). Minor faults that transect the trend of the major longitudinal faults (Plate 1) are also found in the segment. A porphyritic andesite body occupies the syncline in the eastern part of the Kekekabic Lake segment while tuff and agglomerate occupy the syncline in the western part. Porphyritic diorite to syenodiorite dikes which are apparently a later phase of the Kekekabic stock, intrude the rocks of the segment as does diabase. Rocks in the Kekekabic Lake segment are estimated to have a minimum thickness of 1200 feet (Plate 2). A total of 63 thin sections from the Kekekabic Lake segment were used for petrographic study.

Description of rock types

Graywacke is the dominant lithology in the Kekekabic Lake segment. The graywackes studied are equally divided between the lithic and feldspathic subtypes. Both subtypes appear to be randomly distributed throughout the segment although the majority of the feldspathic graywackes occur in the eastern end of the segment between Eddy Lake and the Kekekabic Ponds (Plate 1).

Megascopically the lithic and feldspathic graywackes are identical. Both are light orange to dark green on the weathered surface, green on the fresh fracture, and medium-grained (avg. clast size 0.5 to 1.0 mm). Graywacke beds range from 1 to 27 cm in thickness and have an average thickness of 3 cm. In outcrop nearly all of the graywacke beds are graded from medium- to fine-grained. Interbedded with the graywackes are green slates which are approximately 2 cm in thickness. Some graywacke outcrops in the Kekekabic

Lake segment also contain ferruginous slates. These slates are purple on the weathered surface, red on the fresh fracture, and have an average thickness of 1.0 cm. The ferruginous slates are rhythmically interbedded with graywackes and slates (Fig. 25).

Figure 25: Photograph of ferruginous slate interbedded with graywacke and green slate. SW1/4, NW1/4, Sec. 35, T. 65N., R. 7W.

Lithic graywackes

In thin section, Figure 26, the lithic graywackes are angular, poorly sorted, and medium- to coarse-grained (avg. clast size 1.0 to $>$ 2.0 mm) with some fragments up to 3 mm in diameter. In contrast, the lithic graywackes of the Spoon Lake segment are fine- to medium-grained in thin section (avg. clast size $<$0.5 to 1.0 mm). The lithic graywackes of the Kekekabic Lake segment also have an abundance of hornblende andesite fragments (Fig. 12) while the lithic graywackes of the Spoon Lake segment do not.

Figure 26: Photomicrograph of lithic graywacke (one polar). Hornblende andesite fragments at center and upper right, two plagioclase clasts at left, matrix of predominantly hornblende and smaller rock fragments. SW1/4, SE1/4, Sec. 29, T. 65N., R. 6W.

Table 5 shows the modal analyses of eleven lithic graywacke samples studied. Dacite, andesite, and hornblende andesite are the predominant rock fragments in the lithic graywackes of the Kekekabic Lake segment. Plutonic fragments which resemble and apparently were derived from the Saganaga Tonalite were found in one sample which was collected from the NE1/4, NE1/4, NW1/4, of Sec. 32, T. 65N., R. 6W. Lithic graywackes of the Kekekabic Lake segment are rich in hornblende compared to those of the Spoon Lake segment. In fact, samples collected from the western boundary of the segment, near the portage to Pickle Lake (Plate 1), show a gradation in hornblende content. The percentage of hornblende in the graywackes increases north to south from the south shore of Pickle Lake to the contact with the hornblende tuff and agglomerate (numbers 1, 8, 10, and 11 respectively, Table 5). Since the graywackes are folded into a syncline and lie beneath the tuff and agglomerate, the hornblende content actually increases as the stratigraphy becomes younger. This stratigraphic gradation seems to record the increasing development of hornblende crystals (presumably in a magma chamber) preceding a major episode of extrusion (hornblende andesite) and explosive volcanism (tuff and agglomerate).

Quartz within the lithic graywackes is predominantly common quartz with some volcanic and polycrystalline quartz also seen. Plagioclase clasts are generally elongate, polysynthetically twinned, and partially altered to sericite. The plagioclase can be zoned and antiperthitic in some thin sections. Orthoclase percentages were estimated by staining, but in some cases ortho-

TABLE 5--HORNBLENDE-RICH LITHIC GRAYWACKE MODES FROM KEKEKABIC LAKE SEGMENT

*Modal Analyses of Hornblende-rich, Lithic Graywackes, Kekekabic Lake Segment

	1	2	3	4	5	6	7	8	9	Tuffaceous, Lithic, Graywacke 10	11
Undulose common qtz.	11.5	7.8	0.4	0.8	0.3	0.2	1.5	—	0.6	—	0.2
Volcanic quartz	1.5	1.0	—	—	—	—	—	—	0.3	—	—
Polycrystalline quartz	0.9	1.0	0.6	0.8	—	—	—	—	—	—	—
Plagioclase	18.6	17.2	11.6	16.2	18.0	14.0	4.8	1.0	13.1	—	0.8
! K-feldspar	4.2	2.9	0.4	—	2.0	7.8	—	—	3.0	—	—
Rock Fragments:											
Rhyolite	1.8	6.8	0.4	—	0.2	0.3	—	—	0.5	—	—
Dacite	9.2	10.3	0.8	0.6	0.5	0.2	—	—	0.8	—	0.3
Andesite	8.8	11.4	4.8	0.2	4.3	8.0	5.5	1.2	1.8	—	4.1
Basalt	0.5	3.7	—	—	—	—	—	—	—	—	—
Hbl Andesite	2.5	10.6	35.4(a)	25.6	25.0	13.5(a)	4.8	0.8	22.3	4.5(a)	4.6
Poly Hbl	—	—	6.8	1.4	2.0	1.3	—	—	—	—	7.6
Recrystallized vol.	4.0	—	—	—	0.2	—	14.0	5.2	—	—	—
Siltstone	5.3	—	3.8	28.8	—	—	—	—	—	—	—
Plutonic	1.5	3.6	—	0.4	0.8	0.5	—	—	2.5	—	—
Total rock fragments:	33.6	46.4	52.0	57.0	33.0	25.8	24.3	7.2	27.9	4.5	16.6
Hornblende	8.3	8.8	15.0	17.0	25.3	30.2	36.8	37.2	39.3	71.2	51.5
Chlorite	2.5	2.4	3.0	—	3.1	2.6	0.8	—	3.0	—	5.6
Epidote	6.3	—	0.8	0.6	0.5	4.3	1.0	—	0.3	—	0.8
Sericite	—	—	—	—	—	0.2	—	—	—	1.6	1.3
Carbonate	1.0	—	—	—	—	—	—	—	—	—	—
Matrix	7.0	8.5	11.4	7.0	15.0	14.2	30.2	33.2	11.5	21.8	20.5
Opaques	0.6	—	—	0.4	—	0.2	—	—	—	—	0.8
Others	3.8	3.2	4.8	0.2	1.8	0.5	0.8	—	0.6	0.8	0.8

* 600 points per thin section
! K-feldspar percentage aided by staining
(a) Includes minor hornblende trachyte-latite-trachyandesite

clase clasts were positively identified because of their perthitic nature. Lithic graywackes of the Kekekabic Lake segment are relatively rich in orthoclase compared to the lithic graywackes of the Spoon Lake segment, containing zero to 4%.

The matrix in the lithic graywackes is a mixture of smaller rock fragments, plagioclase and quartz clasts, chlorite, and epidote. Matrix within some of the lithic graywackes took a slight yellow stain. This may be caused by large amounts of sericite in the matrix and/or possibly some felsic tuffaceous material. The lithic graywackes studied were commonly not bedded in thin section.

Feldspathic graywackes

Feldspathic graywackes are angular, moderately to well sorted, and fine-grained (avg. clast size $<$0.5 mm) in thin section. Table 6 shows the modal analyses of eight samples studied. Common quartz is the predominant quartz type with clasts of volcanic and polycrystalline quartz also present. Dacite and andesite are the dominant rock fragments although one sample contains a high percentage of recrystallized fragments. Hornblende is a minor component in the feldspathic graywackes. Plagioclase clasts are polysynthetically twinned and altered to sericite or, in some cases, carbonate. Orthoclase percentages were estimated by staining, but in some cases orthoclase clasts were positively identified because of their perthitic nature. The feldspathic graywackes of the Kekekabic Lake segment are relatively rich in orthoclase compared to the feldspathic graywackes of the Spoon Lake segment,

TABLE 6--MODES OF FELDSPATHIC GRAYWACKES IN KEKEKABIC LAKE SEGMENT

Modal Analyses of Feldspathic Graywackes, Kekekabic Lake Segment

	1	2	3	4	5	6	7	8
Undulose common qtz.	3.5	10.2	3.0	9.2	4.1	18.0	19.2	14.0
Volcanic quartz	—	—	0.8	—	—	—	0.3	0.5
Polycrystalline quartz	—	—	0.8	—	—	2.3	1.6	1.1
Plagioclase	31.2	18.5	15.6	10.8	33.4	11.6	17.5	24.2
! K-feldspar	—	—	3.0	14.3	—	9.5	9.2	8.8
Rock Fragments:								
Rhyolite	—	—	4.6	—	—	0.2	1.2	2.2
Dacite	0.2	0.5	4.2	0.5	—	0.3	1.5	7.3
Andesite	—	0.2	5.6	0.2	1.7	—	2.2	13.5
Basalt	—	—	0.4	—	—	—	—	0.3
Hbl Andesite	—	—	—	—	—	—	—	0.3
Recrystallized vol.	21.8	—	13.6(c)	—	—	—	—	1.0
Siltstone	—	17.8(a)	32.8(c)	11.5(c)	—	—	0.5	3.2
Plutonic	—	—	—	—	—	—	1.2	1.0
Total rock fragments:	22.0	18.5	14.8	0.7	1.7	0.5	6.6	28.3
Hornblende	—	—	4.4	—	—	2.6	—	0.6
Chlorite	4.8	1.0	0.4	—	8.7	0.2	1.5	3.5
Epidote	0.2	—	0.5	4.6	0.5	0.2	0.5	0.3
Sericite	0.2	2.5	—	0.3	—	—	—	—
Carbonate	—	—	1.0	—	—	0.5	—	0.3
Matrix	33.8	30.0	7.8	47.8	42.6	46.6	40.2	14.6
Opaques	—	1.5	0.6	—	0.2	0.8	—	0.9
Others	4.2	17.8(b)	0.8	0.6	8.5(b)	7.0(b)	3.5	2.0

* 600 points per thin section
! K-feldspar percentage aided by staining
(a) Sericite phyllite fragment
(b) Fractures infilled by quartz and carbonate
(c) Refers to beds, not fragments

containing zero to 14%.

The matrix within the feldspathic graywackes is composed of quartz, feldspar, magnetite, and carbonate set in a black (tuffaceous) chlorite-rich paste. The matrix took a stain in some samples. No graded bedding was observed in thin section, but it was seen in outcrop as previously mentioned. Half of the feldspathic graywacke samples studied have a crude bedding.

Mafic tuff

A mafic (basalt or andesite) crystal tuff was studied in two samples collected from the small point on the south shore of Eddy Lake. The point is located in the SW1/4, SE1/4, of Sec. 20, T. 65N., R. 6W. Megascopically the tuff samples could not be distinguished from previously described graywackes. Therefore, tuff was not used in the field to describe the samples collected but only after petrographic study had revealed the samples to be crystal tuffs. The tuff beds are approximately 1.5 cm in thickness and are not graded. Interbedded with the tuffs are beds of green slate.

Microscopically the tuff samples are fine-grained (avg. crystal size $<$0.5 mm), angular, and moderately to well sorted. The mafic tuff contains predominantly plagioclase crystals surrounded by minor amounts of common undulose quartz and rock fragments (mostly dacite and andesite, some rhyolite). Plagioclase crystals are subhedral, polysynthetically twinned, and partially altered to sericite, carbonate, or sausserite. Only a few of the crystals are broken. The crystal tuff in both thin sections is interbedded with laminae (1 mm in thickness) of siltstone and beds (1 cm in thickness) of tuffaceous slate (Fig. 27). The siltstone is composed of minute quartz and plagioclase clasts set in a carbonate-rich cryptocrystalline (tuffaceous) matrix. Graded bedding was not seen in thin section.

Felsic tuff

A felsic (trachyte or latite) crystal tuff sample was collected from the small point in the SE1/4, SE1/4, SW1/4, of Sec. 29, T. 65N., R. 6W. Again tuff was not used in the field but only after petrographic study. Megascopically the tuff resembles a typical graywacke sample with graded bedding and interbedded green slates.

Microscopically the felsic tuff is medium-grained (avg. crystal size 1 mm), angular, and well sorted (Fig. 28). It contains 28% plagioclase crystals, 24% orthoclase crystals, 8% chlorite, and 21% matrix. Minor amounts of carbonate, opaques, rock fragments (mostly rhyolite, some andesite), and quartz-veins comprise the remainder of the thin section. Approximately 24% of the grains within the sample took a deep yellow stain and therefore feldspars which were not polysynthetically twinned were considered to be orthoclase. The feldspar crystals are subhedral and partially altered to sericite. Some of the crystals are broken. The matrix within the felsic tuff is black (crossed nicols), cryptocrystalline (devitrified glass?) and contains minute feldspar crystals, rock fragments, and spots of chlorite. Bedding is seen in thin section and is defined by the parallel alignment of elongate

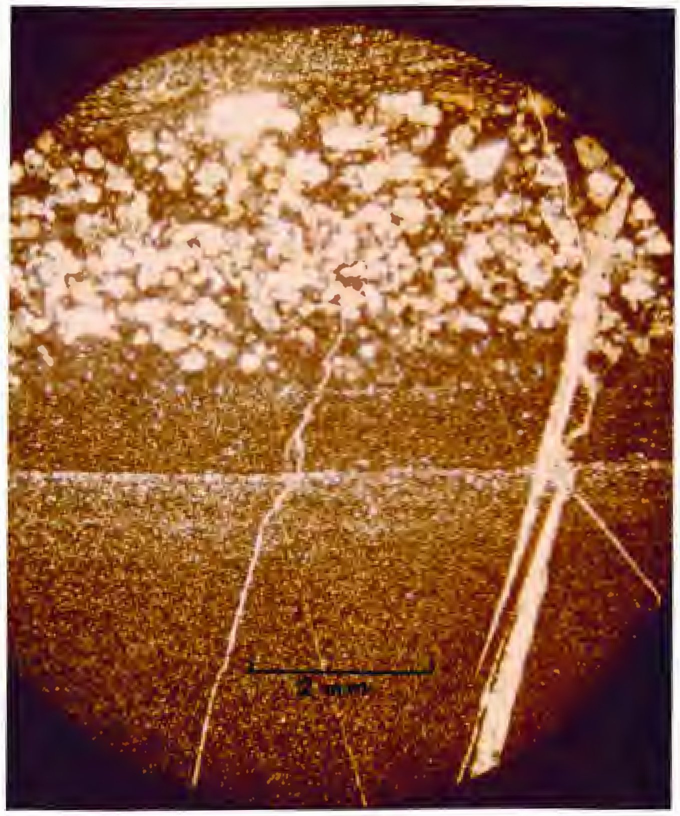


Figure 27: Photomicrograph of an apparent water-laid mafic, crystal tuff (one polar) consisting of highly sericitized and sausseritized plagioclase crystals interbedded with siltstone (coarser-grained) and slate. SW1/4, SE1/4, Sec. 20, T. 65N., R. 6W.

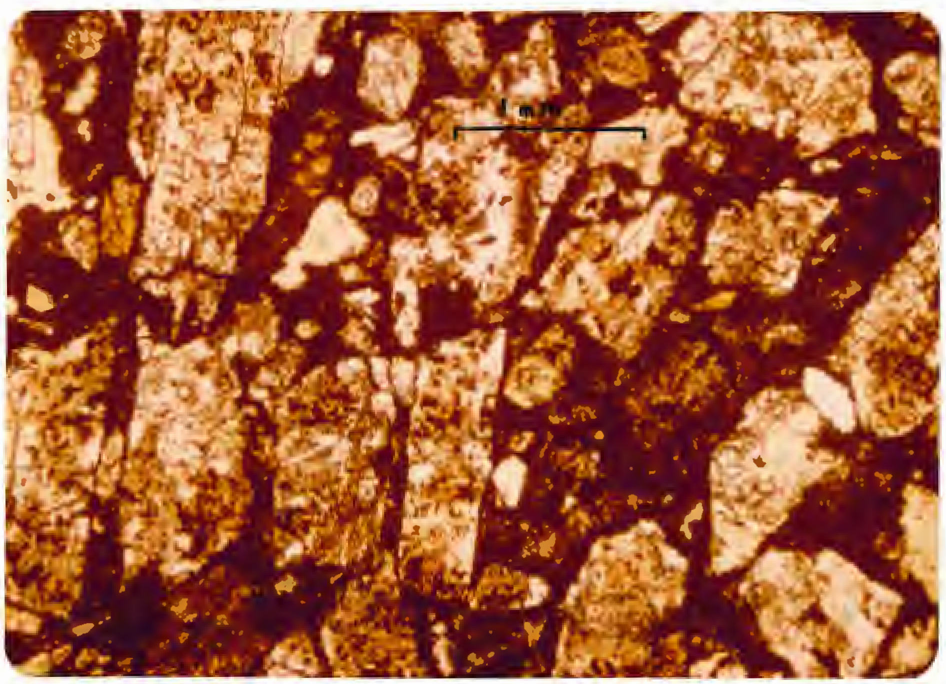


Figure 28: Photomicrograph of an apparent water-laid felsic, crystal tuff (one polar). Note broken crystals. SE1/4, SE1/4, SW1/4, Sec. 29, T. 65N., R. 6W.

feldspar crystals. Graded bedding was not observed in thin section.

Both the mafic and felsic tuffs appear to be interstratified within the graywackes and slates of the Kekekabic Lake segment. The presence of slates between tuff beds may indicate the mafic and felsic crystal tuffs were: a) deposited directly into water, or b) carried downslope by turbidity currents after deposition on the flanks of a volcanic pile. However, no Bouma sequences were observed between tuff beds and hence turbidity currents are herein not considered to have transported the tuffs.

Porphyritic augite-hornblende andesite

Four samples of porphyritic augite-hornblende andesite were studied petrographically. All of the samples were collected from the central inland area between Eddy Lake and the Kekekabic Ponds (Plate 1). Two are located in the SW1/4, SW1/4, SW1/4, of Sec. 21, T. 65N., R. 6W., while the other two are located in the NE1/4, of Sec. 29, T. 65N., R. 6W. Megascopically the augite-hornblende andesite is green on both the weathered surface and fresh fracture. It contains approximately 10% anhedral mafic phenocrysts (3 mm in diameter) and 90% aphanitic groundmass. The weathered surface forms a rind (up to 5 mm thick) above the unweathered rock and contains pits which were presumably formed by the weathering out of phenocrysts. Obvious volcanic features such as amydules were not seen in outcrop; however, a few hexagonal cooling columns were seen in one outcrop (Fig. 29). The outcrop is located in the NE1/4, SW1/4, NE1/4, of Sec. 29, T. 65N., R. 6W. The columns were

Figure 29: Photograph of a hexagonal cooling column (2-d) in augite-hornblende andesite. NE1/4, SW1/4, NE1/4, Sec. 29, T. 65N., R. 6W.

only seen in 2-dimensions and are approximately 7 cm in diameter. Augite phenocrysts were not recognized in the field and therefore augite was used in the name only after petrographic study.

The augite-hornblende andesite is situated within the major syncline that encompasses the entire Kekekabic Lake segment (Fig. 30) and has an estimated minimum thickness of 225 feet. The contact between the augite-hornblende andesite and the underlying graywackes, slates, and tuffs was observed at the eastern terminus of the syncline and along its southern flank. The contact in both cases showed the augite-hornblende andesite to lie conformably above the sedimentary rocks.

Andesite is used as a general term to describe the composition of the porphyritic augite-hornblende andesite samples col-

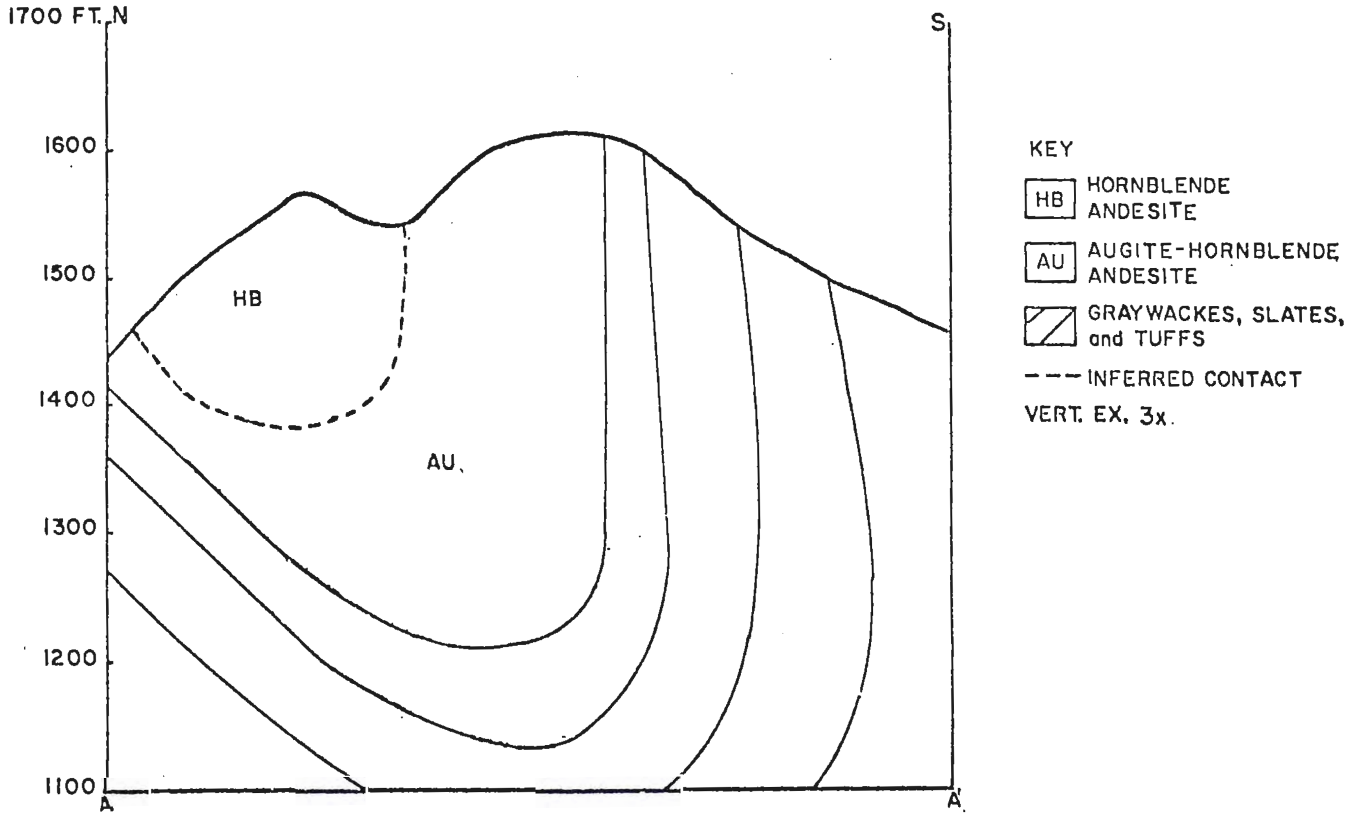


Figure 30: Inferred geologic cross-section A-A' (Plate 1) across area of study (north to south).

lected. No chemical analyses or subsequent chemical classification were done on the samples studied to determine if they were indeed andesitic.

A total of four thin sections were used for petrographic study (Table 7). In thin section, the augite-hornblende andesite is holocrystalline, glomeroporphyritic to porphyritic, hypidiomorphic, amygdaloidal, and has a microcrystalline groundmass. Phenocrysts consist predominantly of clusters of equant augite and minor amounts of elongate, subhedral hornblende (Fig. 31). Augite phenocrysts are partially altered to actinolite and chlorite with complete pseudomorphs to chlorite seen in some thin sections. Hornblende phenocrysts commonly show an opaque oxidized rim and are partially or completely altered to chlorite. The groundmass within the augite-hornblende andesite is made up of minute actinolite crystals along with epidote, chlorite, and small feldspar laths. Next to the contact with the underlying graywackes the groundmass is trachytic (Fig. 32) and has abundant feldspar phenocrysts (0.5 mm in diameter). Amygdules (vesicles infilled with quartz and chlorite) contained in the groundmass are least abundant in the samples collected at and above the igneous-sedimentary contact. Moving west from the contact the amygdules increase slightly in number. Therefore, the base of the augite-hornblende andesite is trachytic and is exposed at the eastern terminus of the major syncline. The augite-hornblende andesite thickens, becomes more vesicular (amygdaloidal), and contains cooling cracks to the west or towards the top of the rock body. The augite-hornblende andesite is here considered to be a portion of

TABLE 7--MODES OF AUGITE-HORNBLENDE ANDESITE
IN KEKEKABIC LAKE SEGMENT

*Modal Analyses of Porphyritic Augite-Hornblende Andesite, Kekekabic Lake Segment

	1	2	3	4
‡ Feldspar	9.3	—	—	—
‡‡ Hornblende	3.0	6.3	0.5	1.6
‡‡ Augite	10.3	11.3	17.8	12.8
Chlorite	3.8	2.0	0.5	6.3
Epidote	—	4.3	12.2	3.3
Carbonate	0.6	—	—	—
Amygules	0.5	0.2	4.8	1.0
Opaques	0.7	—	—	—
Groundmass	70.0	74.6	71.8	74.0
Others	1.6	1.2	2.3	0.8

* 600 points per thin section
‡ Phenocrysts in trachytic groundmass; not able to distinguish whether plagioclase or K-feldspar
‡‡ Phenocrysts

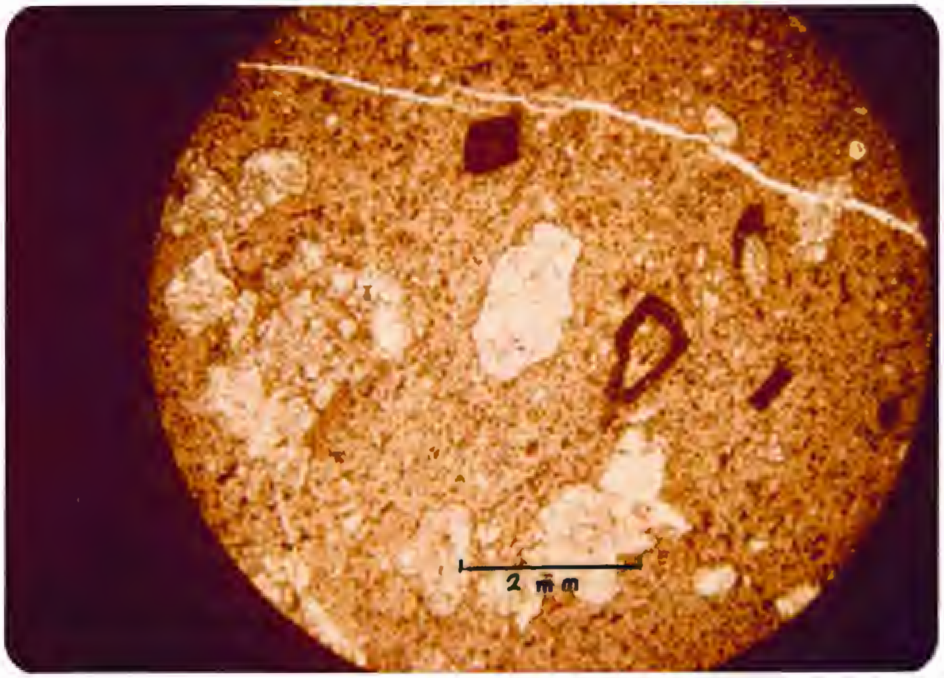


Figure 31: Photomicrograph of glomeroporphyritic augite and porphyritic hornblende in augite-hornblende andesite (one polar). Note microcrystalline groundmass, opaque oxidized rims on hornblende. SW1/4, SW1/4, SW1/4, Sec. 21, T. 65N., R. 6W.

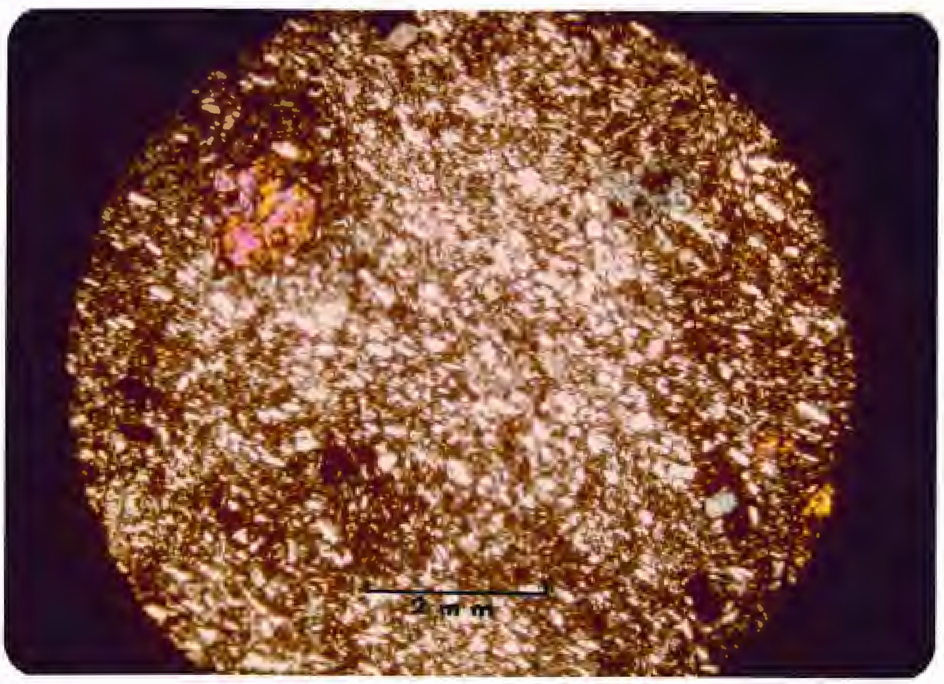


Figure 32: Same but with trachytic groundmass (crossed polars).

a subaerial flow.

No contact relationship was observed in the field between the augite-hornblende andesite and Gruner's (1941) hornblende andesite. However, petrographic and structural analyses have indicated the hornblende andesite lies conformably above the augite-hornblende andesite (Fig. 30).

The augite-hornblende andesite samples took a good yellow stain (trachyte to latite). However, this degree of staining is also seen in the two hornblende andesite samples which were chemically analyzed and classified as andesite and basalt (page 109). Therefore, the stain seen in both the augite-hornblende and hornblende andesite samples is presumably due to a moderate percentage of K_2O in the samples studied; and does not indicate a felsic composition.

Stained augite-hornblende andesite rock fragments were found in a sample collected on the west side of the transverse fault which lies between Eddy Lake and the Kekekabic Ponds (Plate 1). Included in the sample were stained hornblende andesite fragments as well as minor dacite, mafic, and rhyolite fragments. The rock is coarse-grained (avg. clast size 3.5 mm), angular, and poorly sorted. It is apparently a volcanic breccia that is interstratified between flows and was formed by local erosion of the porphyritic augite-hornblende and hornblende andesites subsequent to extrusion.

Porphyritic hornblende andesite

Porphyritic hornblende andesite is the most conspicuous rock type within the Kekekabic Lake segment. The igneous body has an approximate strike length of 2.5 miles (Plate 1) and lies in the major syncline of the Kekekabic Lake segment. The hornblende andesite has an estimated thickness of 150 feet at the eastern terminus of the syncline (Fig. 30) but thickens to the west where it is approximately 600 feet thick. Actual contact relationships between the hornblende andesite and the underlying augite-hornblende andesite were not observed.

Megascopically the hornblende andesite is composed of two distinct rock types which apparently represent two separate subaerial flows. The hornblende andesite within the extreme southeast corner of Sec. 20 and the N1/2, of Sec. 29, T. 65N., R. 6W., (Plate 1) is light pink to purple on the weathered surface and dull red on the fresh fracture. Hornblende andesite exposed in Sec. 30, T. 65N., R. 6W., and the E1/2, of Sec. 25, T. 65N., R. 7W., is greenish-white on the weathered surface and green on the fresh fracture. The section line between Sec's. 29 and 30, T. 65N., R. 6W., is the approximate contact between the stratigraphically lower red hornblende andesite and the stratigraphically higher green hornblende andesite. However, no contact relationship was observed in the field. Both the red and green hornblende andesite contain approximately 10% anhedral to subhedral mafic phenocrysts and 90% aphanitic groundmass. The weathered surface of both andesite types is commonly pitted and forms a rind that may extend up to 5 mm into the unweathered rock. In some samples the weathered surface is bleached white. Mafic phenocrysts were considered to be hornblende in the field and were verified by petrographic analyses. Amygdules were not seen in outcrop but hexagonal columnar joints were found in one outcrop (Fig. 33) which is located in the NE1/4, NW1/4, NW1/4, SE1/4, of Sec. 30, T. 65N., R. 6W. The joints are 8 to 15 cm in diameter, up to 24 cm in length, and plunge 40^{0} to the northwest. The observed columnar joints are similar in appearance to joints that form by rapid cooling of mafic flows or sills (Hyndman, 1972). The size of the columnar joints is related to the rate of cooling and hence, the small columnar joints of the Kekekabic Lake hornblende andesite indicate very rapid cooling, presumably of a subaerial flow. Andesite was used in the field as a general term to describe the chemical composition of the porphyritic hornblende samples collected. Chemical analyses and subsequent chemical classification of two selected samples (page 109) indicates the porphyritic hornblende is andesitic to basaltic in composition.

Porphyritic hornblende andesite was studied in 15 thin sections (Table 8). In thin section, the hornblende andesite is holocrystalline, glomeroporphyritic to porphyritic, hypidiomorphic, amygdaloidal, and commonly has a microcrystalline groundmass (Fig. 34). Phenocrysts within the hornblende andesite are exclusively hornblende with only one thin section containing augite. The hornblende phenocrysts average 1.5 mm in diameter, are partially or completely altered to chlorite (some to muscovite), and appear twinned in thin section (100 as the twin plane). The microcrystalline groundmass contains epidote, chlorite, actinolite, minute plagioclase laths and carbonate. Accessory minerals within the hornblende andesite include magnetite, hematite, ilmenite,

Figure 33: Photograph of a small hexagonal columnar joint in hornblende andesite. NE1/4, NW1/4, NW1/4, SE1/4, Sec. 30, T. 65N., R. 6W.

and apatite.

The red color of the pink to dull red hornblende andesite is due to the presence of extremely small particles of hematite in the groundmass. The hematite occurs throughout the thin sections studied and is here considered to be a primary crystallization product. Stark (1927) concluded some of the hematite may have been derived by the oxidation of magnetite, but chemical analyses of red and green andesite samples (page 109) indicate no difference in their oxidized states (FeO vs. Fe_2O_3). Red hornblende andesite is glomeroporphyritic in the extreme southeast corner of Sec. 20 and porphyritic to the west (N1/2, of Sec. 29). The groundmass within the red andesite is trachytic in Sec. 20 and varies from pilotaxitic to microcrystalline to the west. Hornblende

TABLE 8--HORNBLENDE ANDESITE MODES FROM KEKEKABIC LAKE SEGMENT

*Modal Analyses of Porphyritic Hornblende Andesite
Kekekabic Lake Segment

	1	2	3	4	5	6	7
! Plagioclase	___	20.0	___	___	___	___	___
! Hornblende	17.6	16.0	24.5[a]	15.3	23.0	13.0	14.3
** Muscovite	___	___	___	___	___	___	2.3
Chlorite	1.2	1.8	___	0.2	0.6	0.5	0.6
Epidote	5.0	___	3.8	1.5	3.6	7.0	5.6
Carbonate	___	0.2	___	___	___	___	___
Opaques	___	___	___	___	___	0.2	___
!! Amygdules	2.0	___	0.2	12.0	9.8	2.8	3.0
Groundmass	72.5	57.6	71.3	70.8	62.3	76.0	72.5
Others	1.6	4.2	0.2	0.2	0.5	0.5	1.5

* 600 points per thin section
** Alteration product of Hornblende
! Phenocrysts
!! Vesicles infilled with quartz and chlorite
(a) Includes minor augite with hornblende rims

	8	9	10	11	12	13	14	15
Plagioclase	1.3	0.2	___	___	___	___	___	___
! Hornblende	17.0	27.3[a]	18.5	16.0	30.8	28.3	18.3	11.8
Chlorite	10.8	2.5	0.5	1.3	0.8	2.3	___	0.8
Epidote	0.5	1.0	6.0	8.3	6.2	3.3	___	0.5
Carbonate	1.2	___	___	___	___	2.2	2.3	___
Opaques	___	0.5	0.5	0.3	___	0.3	___	0.2
!! Amygdules	___	___	2.8	2.5	___	1.3	0.3	5.5
Groundmass	67.2	68.0	68.8	68.0	61.0	57.8	77.5	81.2
Others	2.0	___	1.2	2.6	0.3	4.8	1.5	___

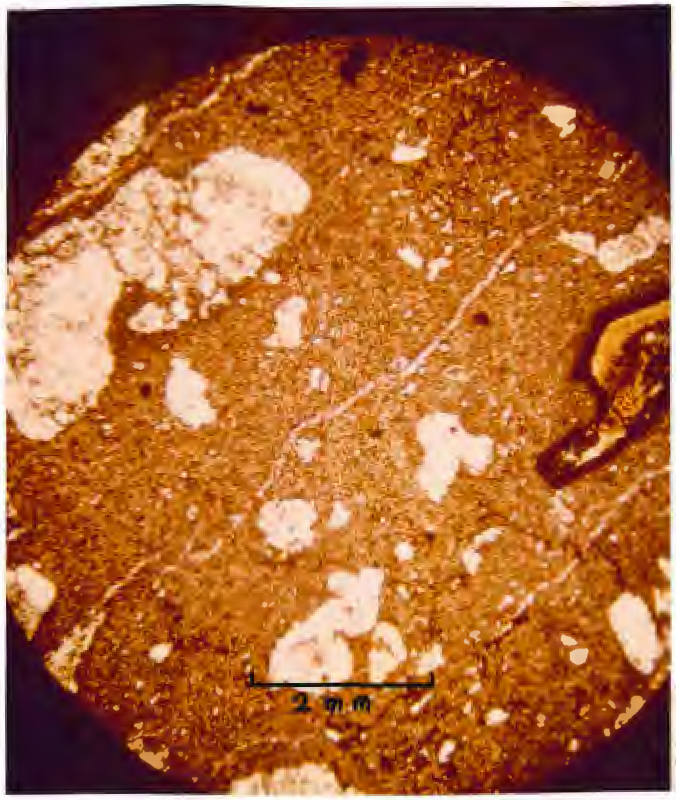


Figure 34: Photomicrograph of glomeroporphyritic and porphyritic hornblende phenocrysts in microcrystalline groundmass (one polar). Note opaque oxidized rim on hornblende. SW1/4, SW1/4, NE1/4, Sec. 29, T. 65N., R. 6W.

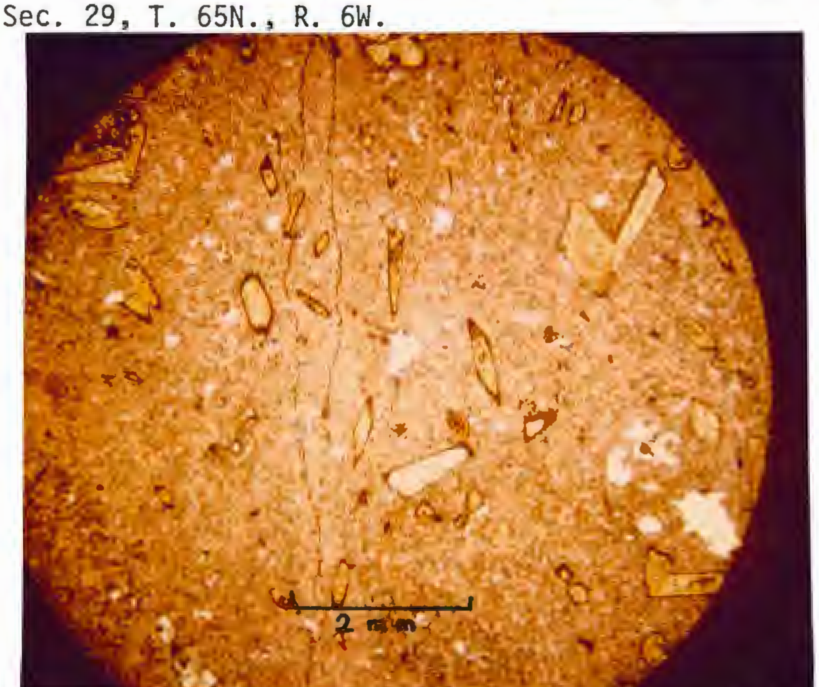


Figure 35: Photomicrograph showing large number of hornblende crystals with oxidized rims, presumably near top of hornblende andesite flow (one polar). SE1/4, SW1/4, NW1/4, Sec. 29, T. 65N., R. 6W.

phenocrysts within Sec. 20 seldom show opaque oxidized rims in thin section. However, to the west, the phenocrysts become more oxidized (Fig. 35) with the greatest percentage of oxidized hornblende phenocrysts occurring near the contact with the green andesite. Oxidation commonly occurs at the tops of flows where air comes in contact with hot lava (Ernst, 1969). Amygdules (vesicles infilled by quartz and chlorite) are scarce in samples collected from the southeast corner of Sec. 20 but increase in abundance to the west (N1/2, of Sec. 29). The red hornblende andesite is considered herein to be a subaerial flow (Fig. 36). The base of the flow is in the extreme southeast corner of Sec. 20 and the top is approximately located at the contact between the red and green andesite. The red hornblende andesite has an approximate thickness of 300 feet.

The green hornblende andesite samples are exclusively glomeroporphyritic. The groundmass within the green andesite is generally microcrystalline, but one sample collected from the extreme NE corner of Sec. 36, T. 65N., R. 7W., is slightly trachytic while another sample collected from the SE1/4, NE1/4, SW1/4, of Sec. 30, T. 65N., R. 6W., is vitrophyric. Hornblende glomerocrysts within the green andesite do not have oxidized rims. Amygdules are abundant in two samples collected from the W1/2, SE1/4, of Sec. 30, T. 65N., R. 6W., (Fig. 37) and decrease in abundance to the west (NE corner of Sec. 36, T. 65N., R. 7W.). The presence of amygdules and columnar joints indicate the green andesite is also a subaerial flow. The top of the flow is exposed in the W1/2, SE1/4, of Sec. 30, T. 65N., R. 7W., while the base of the flow is to the

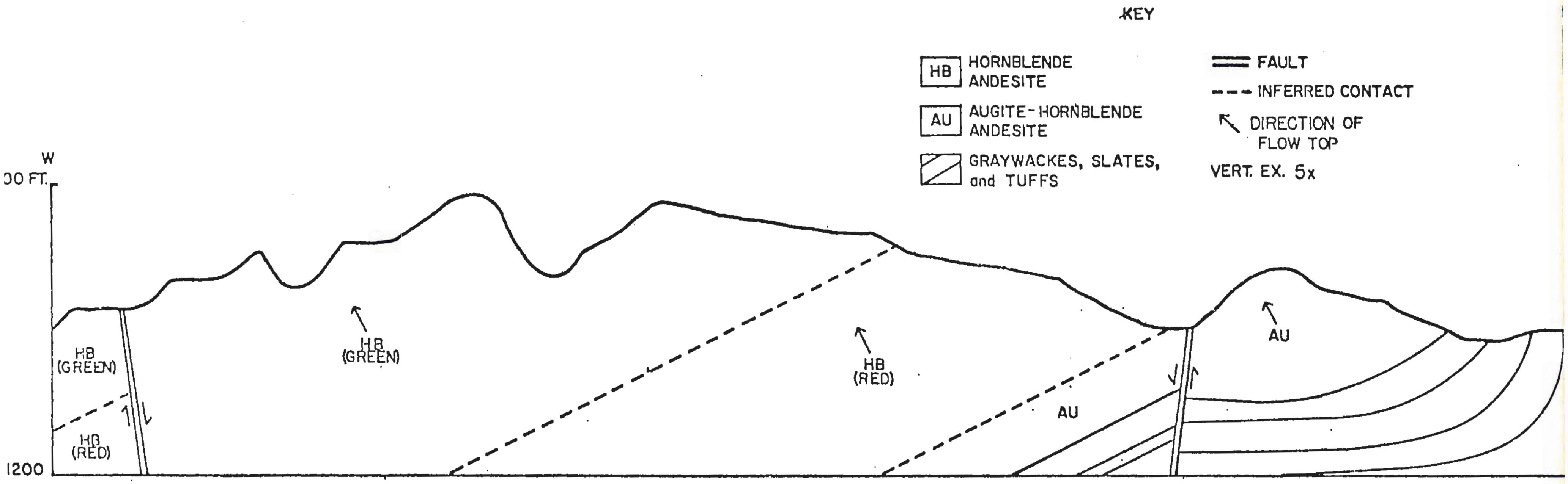


Figure 36: Inferred longitudinal cross-section (west to east) along porphyritic volcanic body, Kekekabic Lake segment. Relative stratigraphic positions of the three subaerial flows are shown.

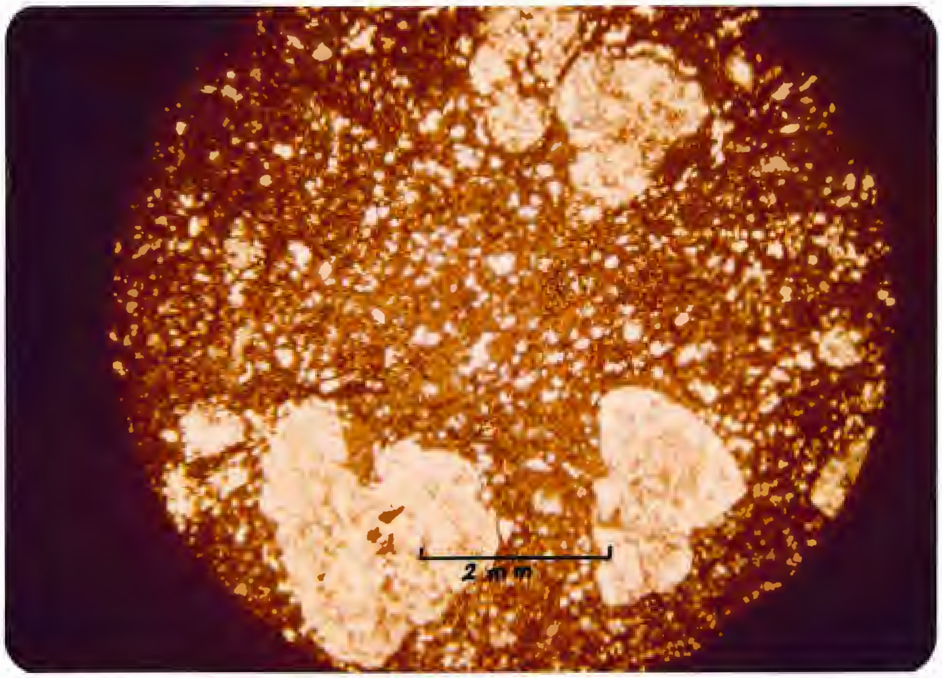


Figure 37: Photomicrograph of abundant amygdules in the groundmass of a glomeroporphyritic hornblende andesite sample (one polar). NE1/4, NW1/4, NW1/4, Sec. 30, T. 65N., R. 6W.

east and is thought to conformably overlie the red hornblende andesite (Fig. 36). The green hornblende andesite is younger than the red andesite and has an estimated minimum thickness of 300 feet.

Both the red and green andesite samples take a light to deep yellow stain. Chemical analyses (page 109) indicate both flows have a relatively high percentage of K_2O compared to an average Cenozoic andesite (Chayes, 1969).

Stained hornblende andesite rock fragments (trachyte-latite-trachyandesite) are found in a few locally derived volcanic breccia samples collected from the Kekekabic Lake segment. The volcanic breccia samples studied are coarse-grained (avg. clast size $>$2.0 mm), contain angular fragments, and are poorly sorted (Fig. 38). They consist predominantly of stained hornblende andesite fragments with minor amounts of hornblende, chlorite, and epidote. Other rock fragments seen in the volcanic breccias include rhyolite, recrystallized volcanic fragments, and plutonic fragments. The volcanic breccia samples were all collected on a longitudinal traverse, west to east, along the hornblende andesite body (Fig. 36). They are epiclastic rocks that are apparently interstratified between flows.

Stained hornblende andesite rock fragments (trachyte-latite-trachyandesite) are also found in a few lithic graywacke samples of the Kekekabic Lake segment. Since the graywackes underlie the porphyritic hornblende andesite body, the stained hornblende andesite rock fragments were apparently eroded from an earlier porphyritic flow or intrusive.

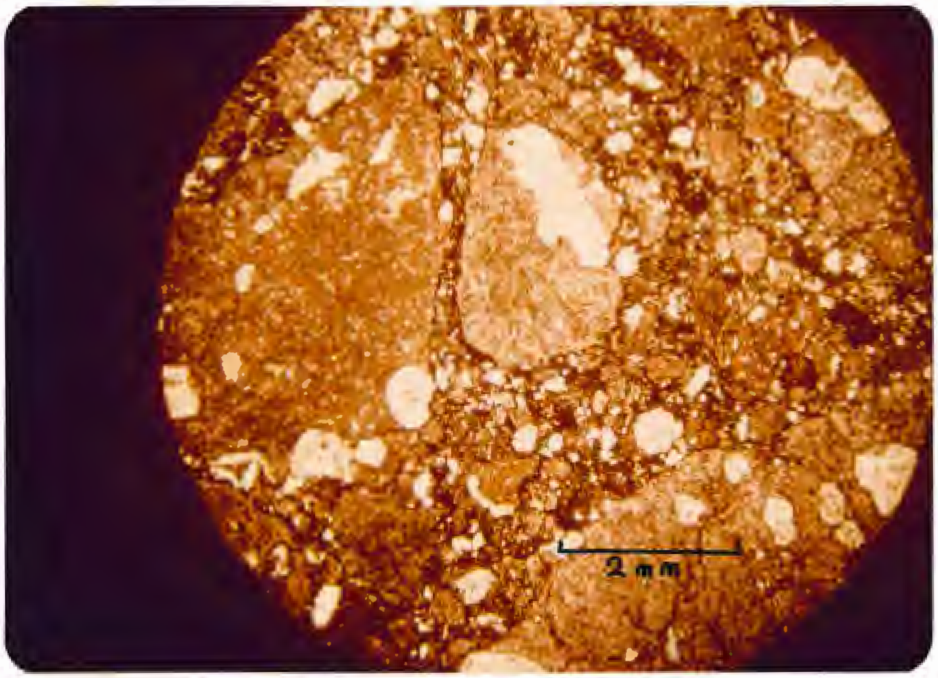


Figure 38: Photomicrograph of volcanic breccia which contains 90% stained hornblende andesite fragments (one polar). NW1/4, SW1/4, SW1/4, Sec. 30, T. 65N., R. 6W.

Tuff and agglomerate

The green hornblende-rich tuff and agglomerate (Fig. 39) exposed along the north shore of Kekekabic Lake (NW1/4, of Sec. 36, and N1/2, of Sec. 35, T. 65N., R. 7W.) consists of a bedded hornblende-rich tuff that contains agglomerate clasts.

Figure 39: Photograph of agglomerate clasts within a green, hornblende-rich tuff. NE1/4, NW1/4, SW1/4, Sec. 35, T. 65N., R. 7W.

The tuff and agglomerate are the most striking rocks within the Kekekabic Lake segment (Plate 1), and "disintegrate to a light green sandy material consisting chiefly of hornblende," (Gruner, 1941). The tuff and agglomerate lie in the southwest-plunging syncline that encompasses the entire Kekekabic Lake segment. The hornblende andesite to the east apparently plunges under the tuff and agglomerate although no actual contact relationship was observed in the field. To the west the tuff and agglomerate apparently pass under Kekekabic Lake (Gruner, 1941).

Megascopically the tuff is green to greenish-white on the weathered surface; green on the fresh fracture, fine-grained (avg. clast size $<$0.5 mm), and shows conspicuous hornblende crystals up to 1 mm in length. In hand specimen the tuff appears to be completely composed of hornblende crystals. The tuff is bedded (avg. bed thickness 2 cm) and also cross-bedded (Fig. 40). Individual cross-beds are 6 to 10 cm wide and 23 to 50 cm long. A trough cross-bed, 24 cm wide and 100 cm long, was also found in one outcrop.

The agglomerate clasts are green on both the weathered surface and fresh fracture, appear rounded in outcrop (angular in thin section), and range from 1 to 23 cm in diameter (avg. clast size 3 cm). Megascopically the agglomerate clasts appear identical to the tuffaceous matrix.

Erosion has produced smooth, curving hollows in the tuff and agglomerate outcrops which gives them a sculptured appearance (Fig. 41). Megascopic inclusions in the tuff and agglomerate include a block of slate, 1 meter in length, as well as a lighter-colored tuff fragment (Fig. 42). In addition, an earlier-formed, rounded agglomerate boulder (30 cm in diameter) was found incorporated into the tuff and agglomerate of the present study (Fig. 43). The earlier agglomerate boulder contains rounded to elongate clasts, 6 cm in diameter, and apparently was formed, eroded, and redeposited in the Kekekabic Lake segment.

Microscopically the tuff contains 60% hornblende crystals, 13% muscovite (alteration product), 1% augite, and 25% matrix.

Figure 40: Photograph of hornblende tuff showing bedding and cross-bedding. NW1/4, SW1/4, NW1/4, Sec. 36, T. 65N., R. 7W.

Figure 41: Photograph of tuff and agglomerate outcrop showing smooth, curving hollows formed by wave erosion. NE1/4, SE1/4, NW1/4, Sec. 36, T. 65N., R. 7W.

Figure 42: Photograph showing lighter-colored tuff fragment in Kekekabic Lake tuff and agglomerate. NE1/4, SE1/4, NW1/4, Sec. 36, T. 65N., R. 7W.

Figure 43: Photograph of rounded agglomerate boulder in Kekekabic Lake tuff and agglomerate. NE1/4, NW1/4, SW1/4, Sec. 35, T. 65N., R. 7W.

Hornblende crystals are subhedral elongate blades that are zoned and have fibrous, actinolite overgrowths (Fig. 44). The overgrowths are herein considered to be metamorphic in origin. Matrix within the one tuff sample studied is composed of chlorite, epidote, muscovite, and minute hornblende crystals.

Three thin sections of agglomerate clasts were studied. The clasts are holocrystalline, porphyritic, and hypidiomorphic to panidiomorphic. In two thin sections the groundmass is granular (Fig. 45) while in the other it is microcrystalline (Fig. 46). Vesicles contained in the one thin section are infilled by quartz, calcite, and chlorite. Phenocrysts within all three samples studied are exclusively hornblende.

The agglomerate clasts are not similar to the porphyritic hornblende andesite flows within the Kekekabic Lake segment. Hence, the clasts were not derived from the andesite flows, but are accidental lamprophyre fragments (personal communication, J. C. Green, 1978) which were deposited in the basaltic hornblende tuff. Lamprophyre dikes are associated with the Saganaga Tonalite to the northeast and the Snowbank batholith to the southwest (Sundeen, 1936). In both batholiths, the dikes are predominantly hornblende lamprophyres which contain hornblende phenocrysts. Textures within the hornblende lamprophyres may be granular or porphyritic. The lamprophyre dikes are thought to be cogenetic with both the Saganaga and Snowbank batholiths (Sundeen, 1936).

Hornblende phenocrysts within the agglomerate clasts are generally elongate, subhedral to euhedral with some crystals exhibiting the pseudohexagonal amphibole cross-section. The pheno-

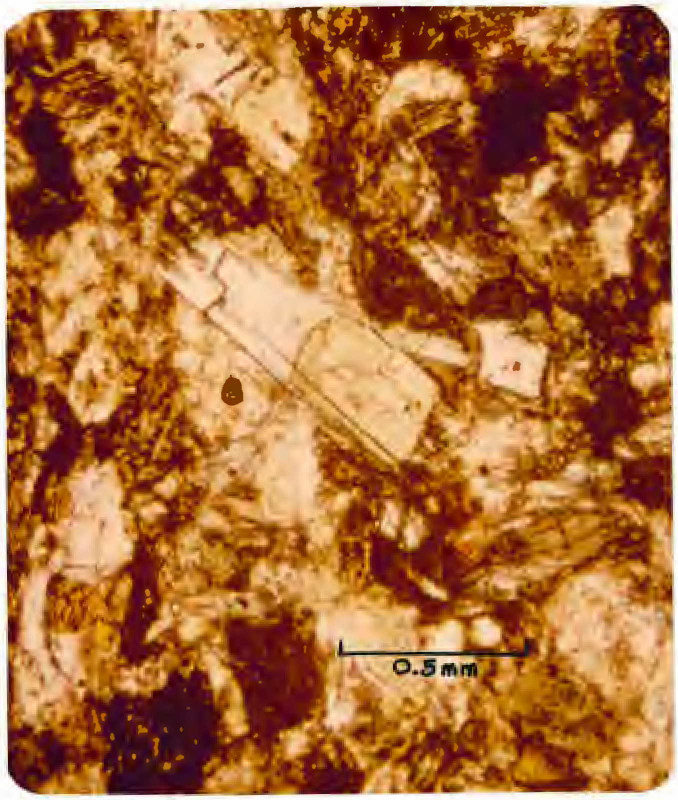


Figure 44: Photomicrograph of hornblende-rich tuff (one polar). Note the metamorphic overgrowths on the hornblende crystals. NE1/4, SE1/4, NW1/4, Sec. 36, T. 65N., R. 7W.

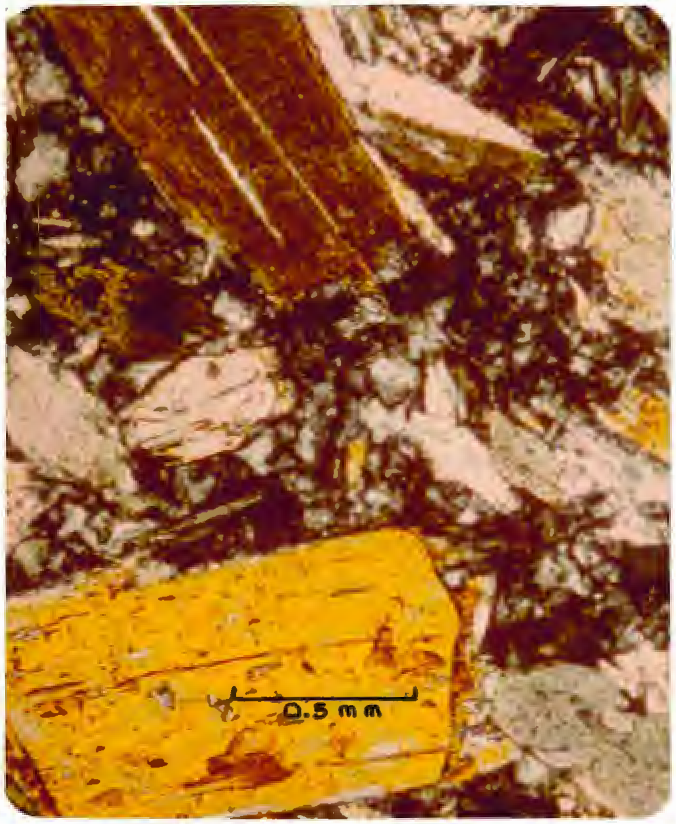


Figure 45: Photomicrograph of agglomerate clast showing phenocrysts of hornblende surrounded by granular groundmass. NE1/4, SE1/4, NW1/4, Sec. 36, T. 65N., R. 7W.

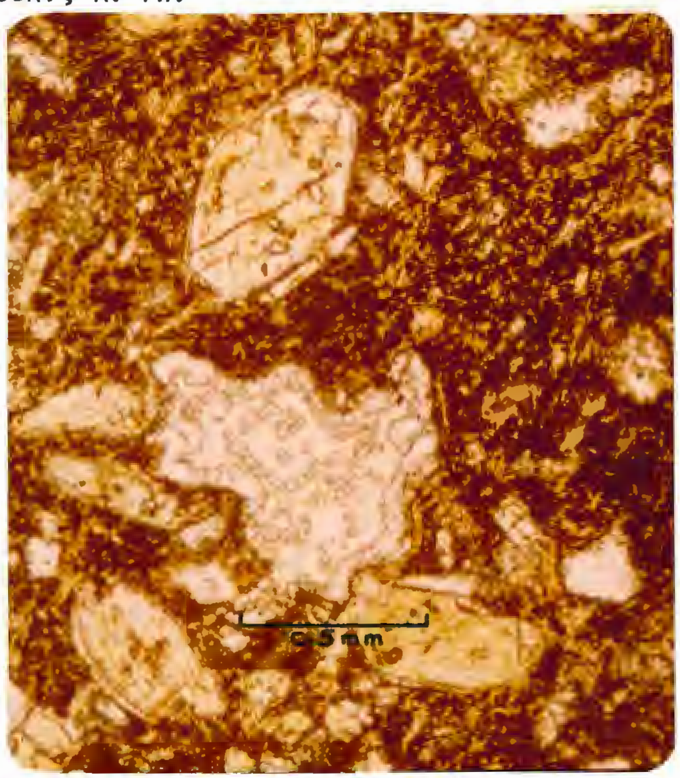


Figure 46: Same but with microcrystalline groundmass and amygdules. NE1/4, SE1/4, NW1/4, Sec. 36, T. 65N., R. 7W.

crysts average 0.5 mm in length, have metamorphic overgrowths, and are zoned. Hornblende phenocrysts comprise 40 to 70% of the three agglomerate samples studied.

The granular groundmass observed in two thin sections is fine-grained ($<$0.06 mm) and consists of plagioclase, orthoclase, quartz, and carbonate in varying ratios. The microcrystalline groundmass is a dark paste of chlorite, epidote, sericite, and minor feldspar.

One hornblende tuff sample was chemically analyzed, classified (page 109), and found to be basaltic in composition. As mentioned, the hornblende tuff is bedded and composed predominantly of hornblende crystals and matrix. It therefore resembles the mafic and felsic crystal tuff samples which were previously described (pages 74 and 75, respectively) as having been deposited directly into water. However, the presence of cross-bedding and trough cross-bedding in the hornblende tuff indicates it has been reworked.

Porphyritic diorite to syenodiorite

Porphyritic intrusive rocks are found in three localities along the north shore of Kekekabic Lake (Plate 1). The intrusive rocks are characterized in outcrop by lineated, white, zoned feldspar laths set in a purple aphanitic matrix (Fig. 47). Of the porphyritic intrusives examined in outcrop, two are approximately 20 feet in length while a third covers a distance of 1000 feet in the northeast corner of Sec. 31, T. 65N., R. 6W. Cross-cutting relationships between the intrusives and the country rock

Figure 47: Photograph of porphyritic syenodiorite outcrop showing characteristic lineation of white, zoned plagioclase phenocrysts. SE1/4, NW1/4, NW1/4, Sec. 31, T. 65N., R. 6W.

Figure 48: Photograph of sub-horizontal columnar joint in porphyritic syenodiorite. SE1/4, NW1/4, NW1/4, Sec. 31, T. 65N., R. 6W.

were not readily apparent, but chilled margins and a sub-horizontal hexagonal cooling column, found in one outcrop (Fig. 48), indicate the porphyritic intrusives are dikes that were intruded vertically.

Megascopically the porphyritic dikes are dark purple on the weathered surface and violet on the fresh fracture. In hand specimen they contain approximately 30% white, subhedral, zoned plagioclase phenocrysts (3 mm to 1 cm in length); 5%, black, elongate hornblende phenocrysts (0.5 to 1.0 mm in length); 5%, clear, anhedral quartz crystals (0.5 to 1.0 mm in diameter); and 60%, purple aphanitic matrix.

Four porphyritic intrusive samples were studied in thin section. Table 9 shows the modal analyses. In thin section, the samples are holocrystalline, porphyritic, and contain a fine-grained ($<$ 0.06 mm) granular to felsitic groundmass (Fig. 49). Plagioclase phenocrysts are elongate, subhedral to euhedral, show complex polysynthetic twinning, and are zoned. They average 2 mm in length and show a dusty alteration. In some thin sections the plagioclase is antiperthitic and/or micrographic. No plagioclase determinations using the Michel-Levy method were possible. Hornblende phenocrysts are subhedral to euhedral and average 0.5 mm in length. Accessory minerals in the porphyritic samples studied include apatite, sphene, and magnetite. The groundmass within the samples consists of plagioclase, orthoclase, quartz, and carbonate in varying proportions. Actinolite needles seen in the groundmass are probably metamorphic in origin. Diorite was distinguished from syenodiorite by staining.

TABLE 9--MODES OF PORPHYRITIC INTRUSIVES
IN KEKEKABIC LAKE SEGMENT

*Modal Analyses of Porphyritic Intrusives,
Kekekabic Lake Segment

	Diorite			Syenodiorite
	1	2	3(a)	4
Undulose common qtz.	___	___	___	5.2
!! Plagioclase	36.3	57.8	21.3	45.2
** Orthoclase	___	___	___	14.6
!! Hornblende	9.3	1.2	24.0	4.3
!! Augite	0.5	3.6	___	0.3
+ Augite & Hbl	2.0	1.8	___	___
Biotite	2.0	___	___	___
Chlorite	___	2.6	___	___
Serpentine	___	___	___	1.6
Carbonate	___	___	1.3	0.3
Opaques	0.5	0.5	___	0.4
Groundmass	47.2	29.3	53.0	26.8
Others	2.2	3.0	0.3	1.2

* 600 points per thin section
** K-feldspar percentage aided by staining
\+ Phenocrysts; augite cores, hornblende rims
!! Phenocrysts
(a) Only 300 points

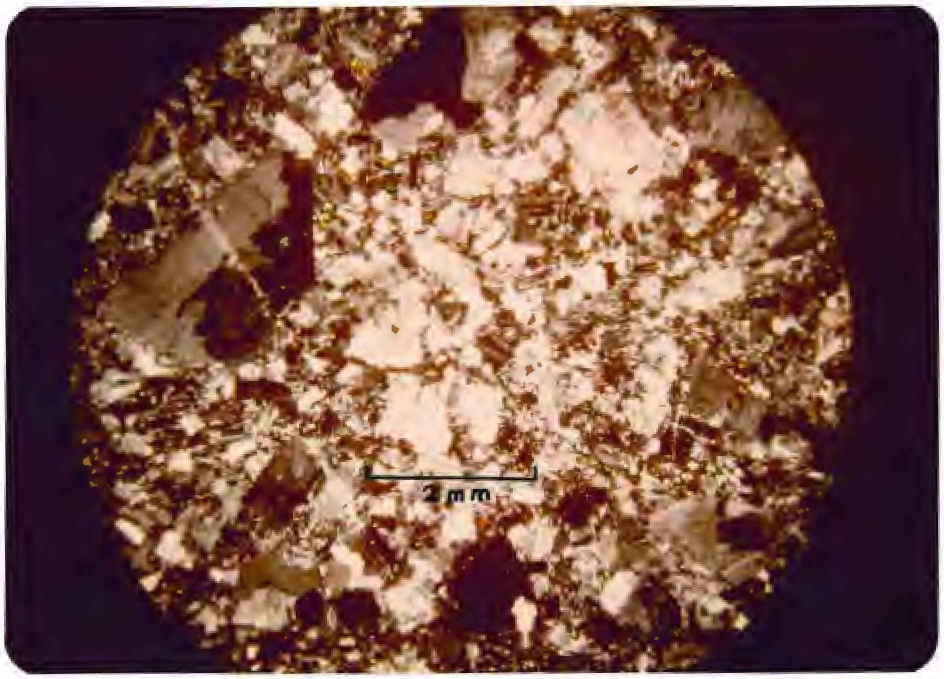


Figure 49: Photomicrograph of porphyritic syenodiorite (crossed nicols). Shows large phenocrysts of plagioclase and smaller phenocrysts of hornblende set in a granular groundmass. SW1/4, SW1/4, SW1/4, Sec. 29, T. 65N., R. 6W.

Diabase

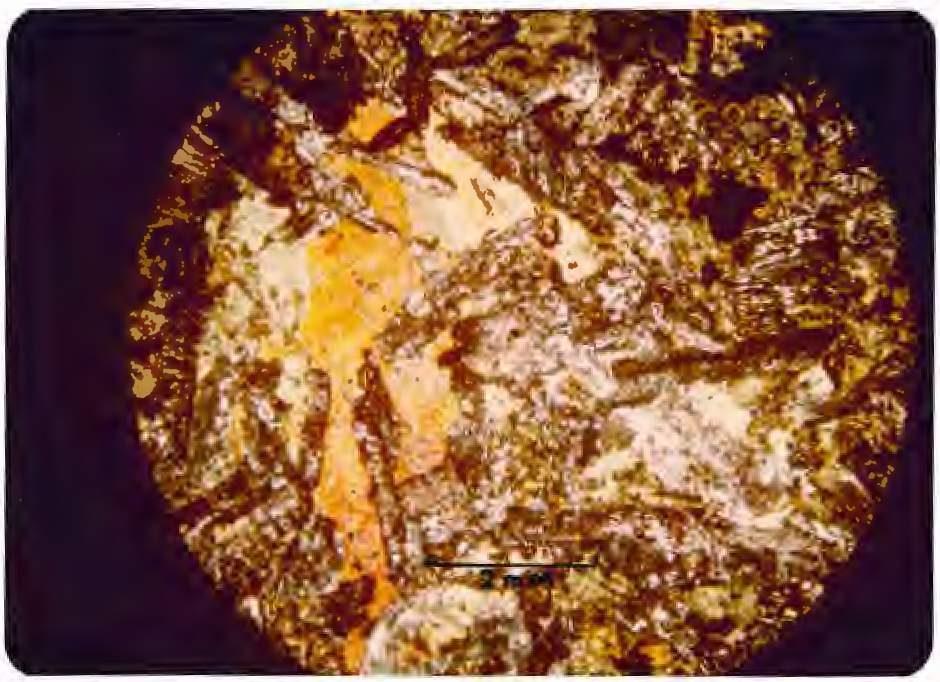
Intrusive diabase is exposed at two locations within the Kekekabic Lake segment. The best exposure is in the SE1/4, SW1/4, of Sec. 29, T. 65N., R. 6W. (Plate 1). The diabase here is approximately 2000 feet long, 75 feet wide, and is apparently continuous with diabase exposed on the south shore of Kekekabic Lake (NE1/4, NW1/4, Sec. 32, T. 65N., R. 6W.). A smaller diabase body is exposed in the NW1/4, NW1/4, of Sec. 32, T. 65N., R. 6W. It is approximately 100 feet long and 20 feet wide. Chilled margins were observed in the larger dike.

Megascopically both exposures are black on the weathered surface and fresh fracture. They contain 60%, elongate, subhedral plagioclase laths (up to 4 mm in length); and 40% aphanitic matrix. Trace amounts of mafic minerals (2 mm in diameter) can also be seen in hand specimen.

Only one diabase sample was studied in thin section. It is holocrystalline, medium-grained (avg. crystal size 3.5 mm), hypidiomorphic, and subophitic. The sample contains 60% felty plagioclase laths, 30% augite, and minor biotite, muscovite (alteration product), and chlorite. Plagioclase crystals are subhedral to euhedral and heavily altered to sericite. No plagioclase determinations using the Michel-Levy method could be made due to the heavy alteration. Augite crystals are anhedral to subhedral and partially or completely altered to amphibole. Accessory minerals within the diabase include ilmenite, magnetite, pyrite, sphene, and apatite.

The diabase dike sample studied from the Kekekabic Lake seg-

Figure 50: Photomicrograph of a fresh, younger, diabase dike sample from the Spoon Lake segment (above); and a heavily altered, older, diabase sample from the Kekekabic Lake segment (below). Both are crossed polars.



ment is highly altered compared to the diabase studied in the Spoon Lake segment (Fig. 50). From this, Stark (1927) concluded that there are two ages of diabase dikes within the present area of study. The oldest diabase is in the Kekekabic Lake segment, the youngest in the Spoon Lake segment.

Chemical analyses

Chemical analyses of three selected samples were done by K. Ramlal of the University of Manitoba. The analyses were done to determine: 1) if the porphyritic hornblende andesite in the present area of study is truly an andesite; 2) if there is any compositional difference between the red and green andesite; and 3) the chemical composition of the hornblende-rich Kekekabic tuff.

The three samples were analyzed for the 13 major oxides using atomic absorption methods. The samples analyzed were selected because of their homogeneous and unsheared structure, and lack of observable metasomatic alteration.

The results of the analyses are shown in Table 10 along with the composition of an average Cenozoic andesite (Chayes, 1969) and an andesite porphyry from the Vermilion district (Green, 1970). The oxides are shown in weight percent and were used to calculate a CIPW norm. In addition, a cation (Chayes) norm was calculated by computer and used for chemical classification of the three samples. Classification was done according to the format described by Irvine and Baragar (1971).

The chemical classification scheme for the common volcanic rocks used by Irvine and Baragar (1971) is shown in Figure 51.

TABLE 10--CHEMICAL ANALYSES OF THREE PORPHYRITIC VOLCANIC SAMPLES

Chemical Analyses, in weight percent, of Selected Samples

	44A	193B	97A	Average Cenozoic Andesite (Chayes, 1969)	Andesite Porphyry Ely (Green, 1970)
SiO_2	56.10	57.05	48.05	58.17	60.95
Al_2O_3	13.56	13.68	10.08	17.26	15.14
Fe_2O_3	2.89	3.15	3.12	3.07	4.34
FeO	3.34	2.92	4.98	4.18	1.16
MgO	8.85	8.35	17.35	3.24	4.38
CaO	4.27	5.39	7.39	6.93	3.32
Na_2O	4.16	2.43	1.67	3.21	5.48
K_2O	2.72	2.81	1.31	1.61	2.12
TiO_2	0.56	0.56	0.44	0.80	0.51
P_2O_5	0.29	0.28	0.16	0.21	0.13
CO_2	0.09	0.04	0.10	———	0.43
MnO	0.09	0.10	0.13	———	0.07
H_2O	2.95	3.16	4.53	———	1.83

44A: "red" hornblende andesite sample. NW1/4, NW1/4, NE1/4, Sec. 29, T. 65N., R. 6W.
193B: "green" hornblende andesite sample. NE1/4, NW1/4, NW1/4, SE1/4, Sec. 30, T. 65N., R. 6W.
97A: hornblende-rich tuff sample. NE1/4, SE1/4. NW1/4, Sec. 36, T. 65N., R. 7W.

CIPW Mineral Norms (weight percent)

	44A	193B	97A
Q	1.17	9.78	———
or	16.07	16.61	7.74
ab	34.13	20.09	12.94
an	10.86	18.37	16.77
di	6.65	5.14	14.88
hy	21.90	20.41	23.85
ol	———	———	13.08
mt	4.19	4.57	4.52
il	1.06	1.06	0.84
ap	0.67	0.65	0.37
cc	0.20	0.09	0.23

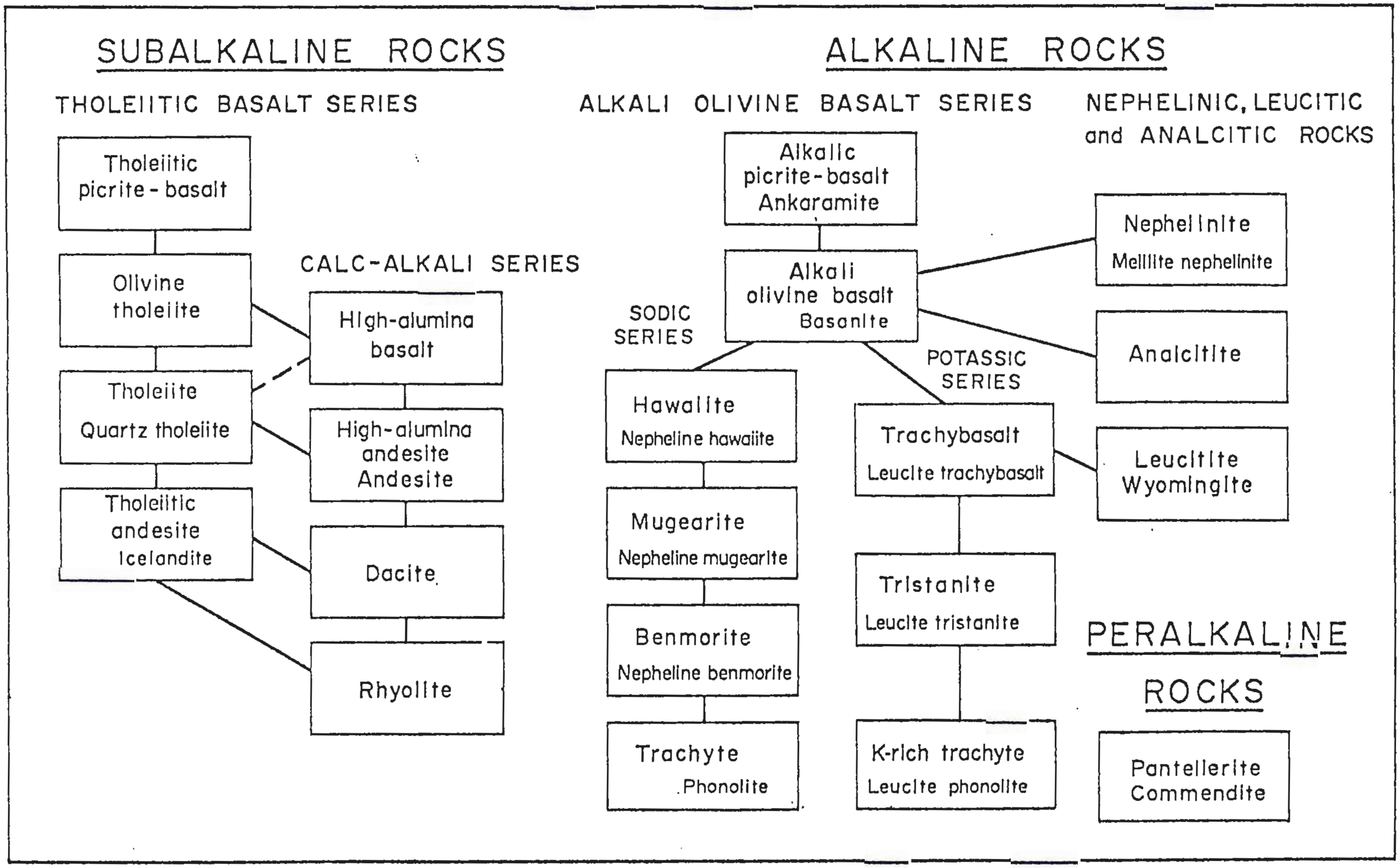


Figure 51: Classification of common volcanic rocks used in this study (Irvine and Baragar, 1971)

The classification is divided into two major groups which correspond to subalkaline and alkaline rocks. The common rock types (i.e., basalt, andesite, etc.) are shown in boxes that are arranged in series within the major groups. Lines joining boxes serve to outline common associations. Using the format of Irvine and Baragar, the rocks from the present area of study were first classified as to alkaline or subalkaline (Fig. 52). To determine whether the rocks belong to the tholeiitic or calc-alkaline series they were plotted on an AFM diagram (Fig. 53). As can be seen, two of the samples (44A and 193B) are calc-alkaline while the hornblende tuff sample (97A) is slightly tholeiitic. Plotting of the normative color index vs. the normative plagioclase composition gives the common name to each of the samples analyzed (Fig. 54). As is shown, the red andesite sample (44A) is indeed andesite, but the green andesite sample (193B) is basaltic in composition while the hornblende tuff sample (97A) has a chemical composition of a tholeiitic basalt. Irvine and Baragar also suggest an An, Or, Ab' plot to distinguish potassium-poor, "average," and potassium-rich variants in the subalkaline rocks (Fig. 55). The green andesite (193B) and hornblende tuff (97A) samples are K-rich. This may account for the staining described in green porphyritic hornblende andesite (basalt) samples. The red andesite (44A) is average in potassium content and plots close to a sodic dacite.

The andesite samples (44A, 193B) analyzed from the two porphyritic hornblende subaerial flows are calc-alkaline and andesitic to basaltic in composition, respectively. Calc-alkaline rocks (basalt-andesite-rhyolite association of Turner and Verhoogen,

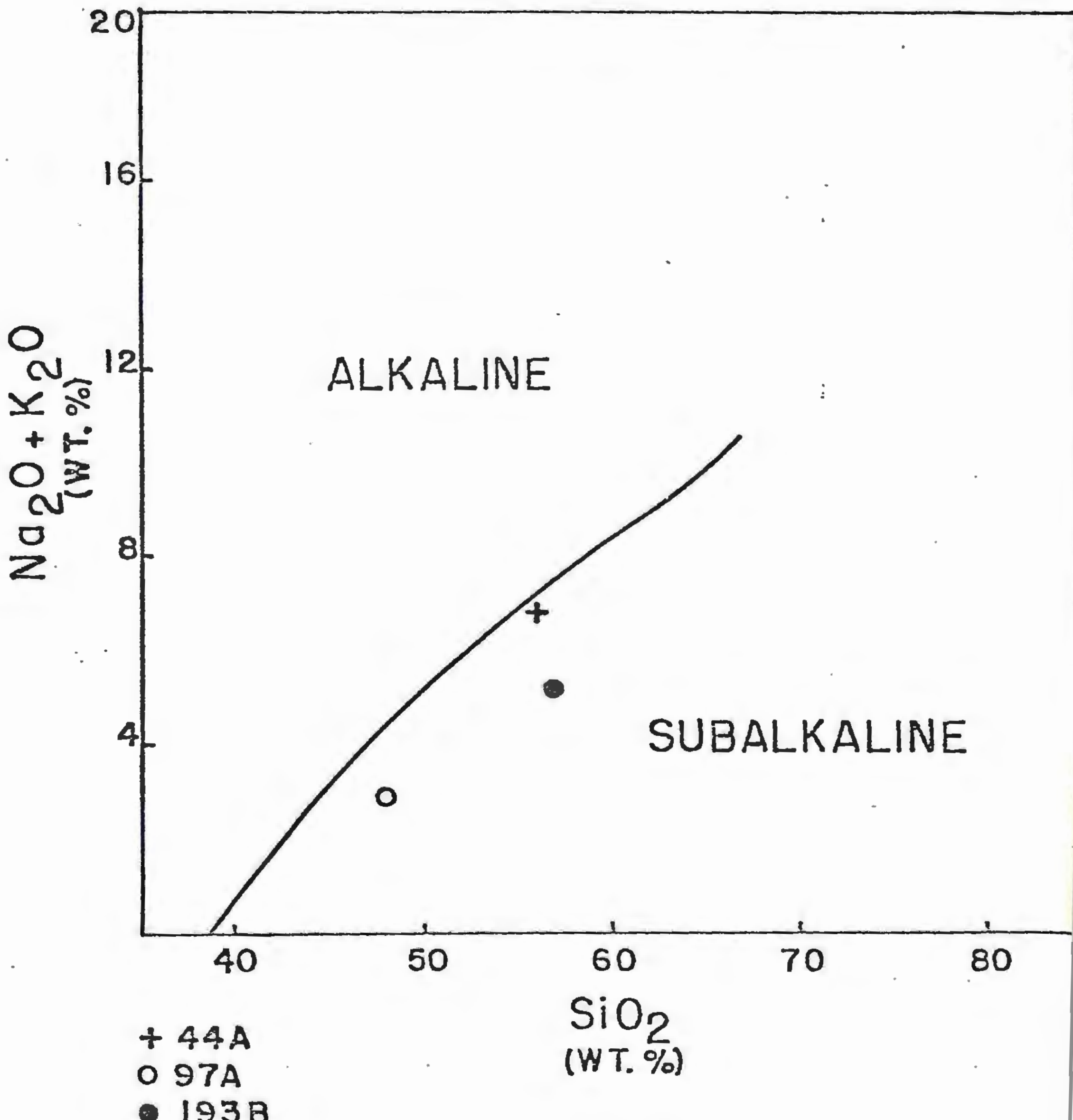


Figure 52: Plot of weight percent $Na_2O + K_2O$ vs. weight percent SiO_2 used to chemically distinguish alkaline from subalkaline rocks (Irvine and Baragar, 1971). 44A=red hornblende andesite; 97A=green hornblende tuff; 193B=green hornblende andesite.

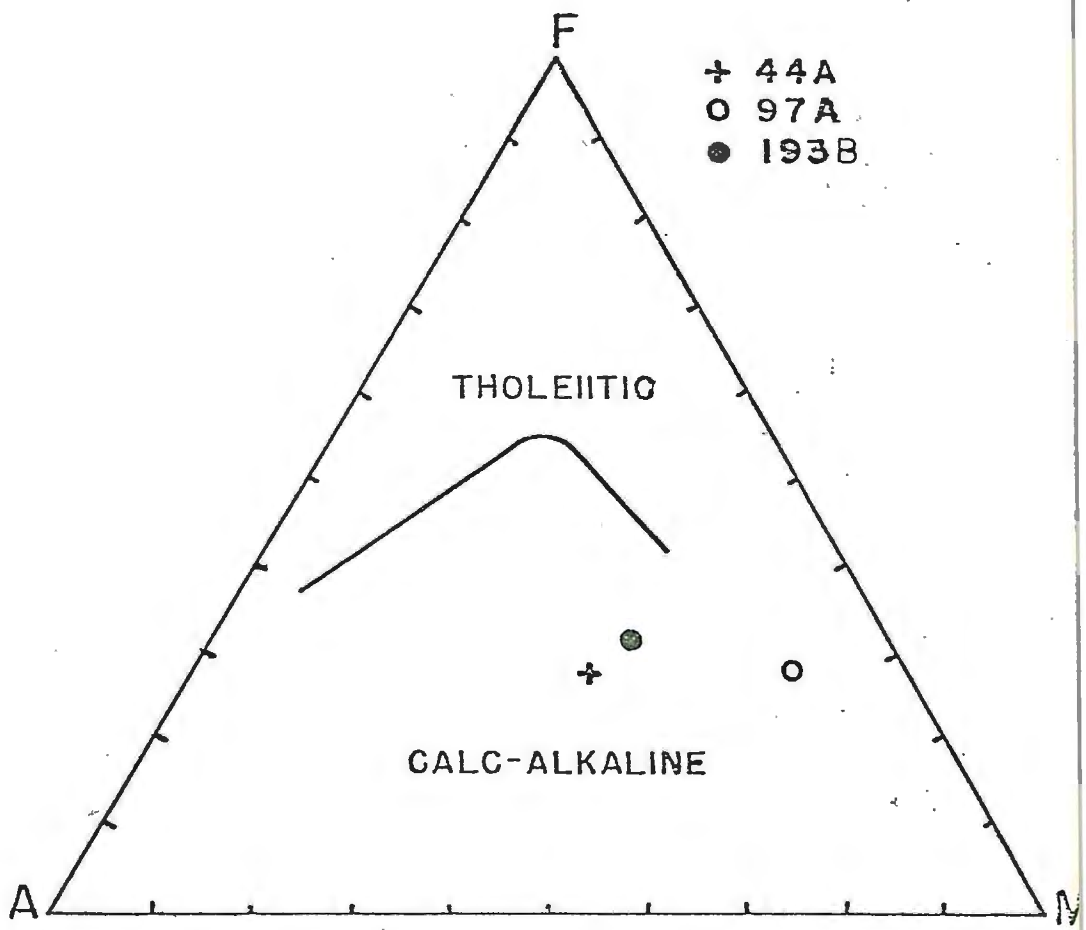


Figure 53: AFM plot used to chemically distinguish tholeiite from calc-alkaline samples (Irvine and Baragar, 1971). A=$Na_2O + K_2O$; F=$FeO + 0.99\ Fe_2O_3$; M=MgO. 44A=red hornblende andesite; 97A=green hornblende tuff; 193B=green hornblende andesite.

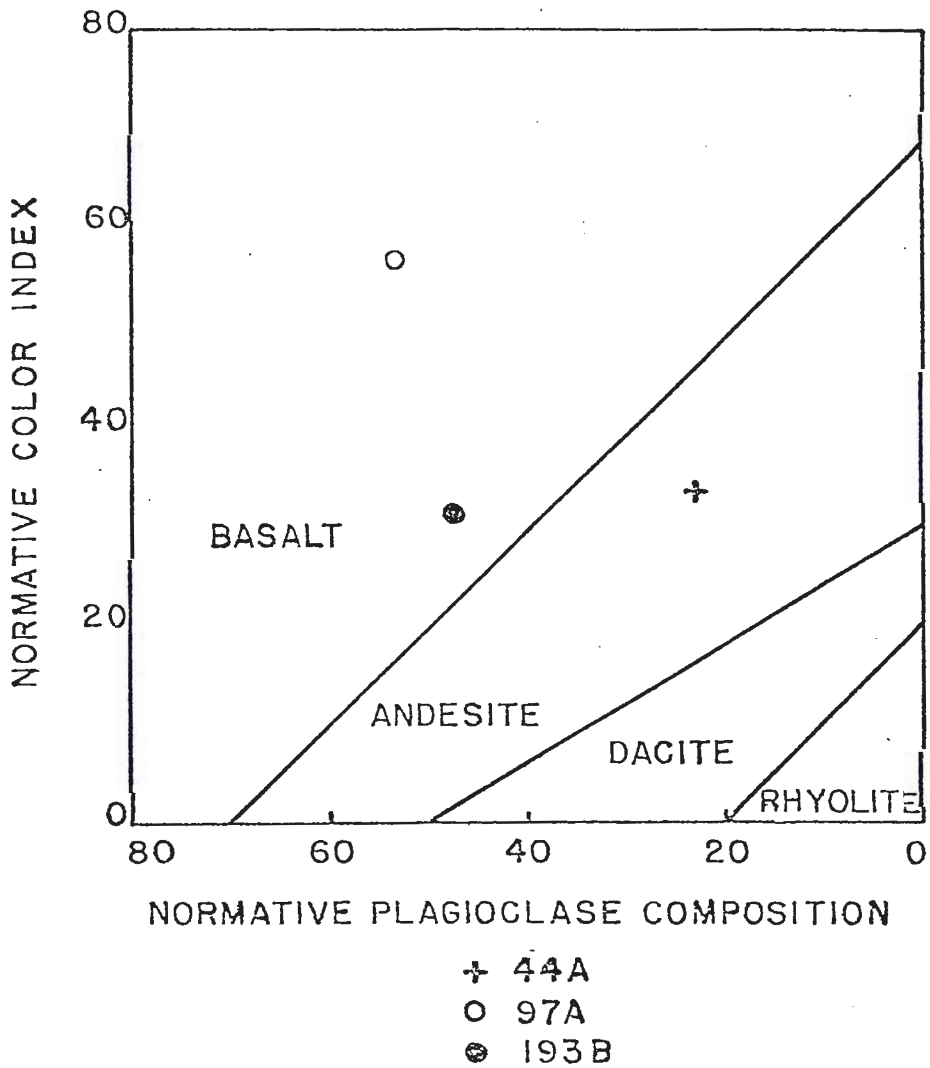


Figure 54: Plot used to identify common volcanic rock types (Irvine and Baragar, 1971). Normative color index = wt. % ol + cpx + mt + il + hm. Normative plagioclase index = an x 100/an + ab + 1.6 ne. 44A = red hornblende andesite; 97A = green hornblende tuff; 193B = green hornblende andesite.

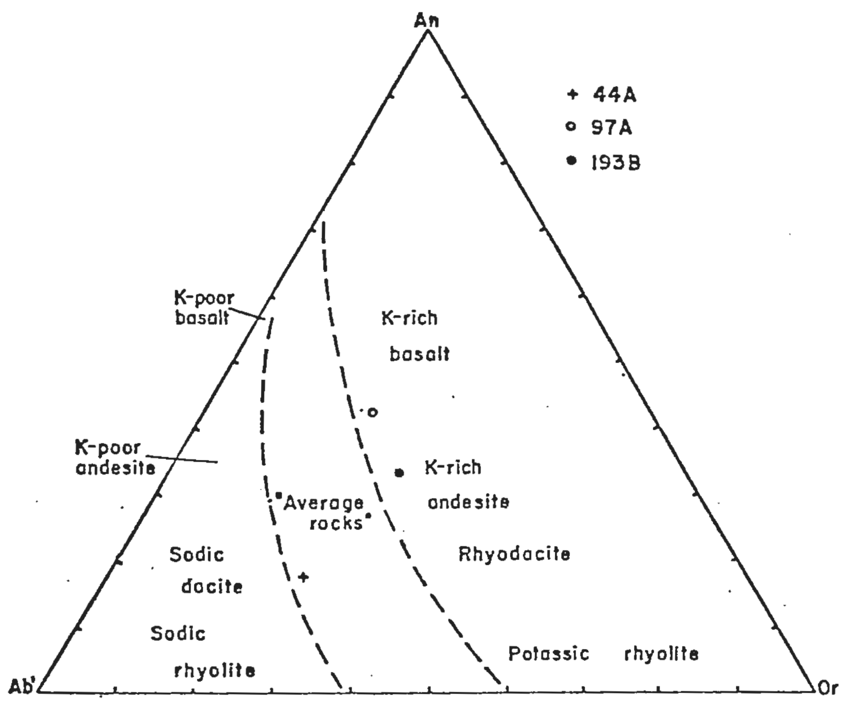


Figure 55: Plot used to chemically distinguish potassium-poor, "average," and potassium-rich variants in subalkaline rocks (Irvine and Baragar, 1971). An, Or, and Ab' all in cation equivalents. Ab' = ab + 1.6 ne. 44A = red hornblende andesite; 97A = green hornblende tuff; 193B = green hornblende andesite.

1960) are typical of continental orogenic belts or island arc systems. The calc-alkaline series includes the chains of prominent stratovolcanoes and associated rocks exemplified by Mount Rainier and other volcanoes of the Cascade range of the western United States. Eruptions within these chains include both lava flows and pyroclastic debris, the latter generally outweighing the former (Hyndman, 1972). Calc-alkaline rocks, including flows and pyroclastics, are abundant in eugeosynclinal successions of Archean greenstone belts where they are associated with pillowed tholeiitic basalts (Irvine and Baragar, 1971). Clifford and McNutt (1971) have described the formation of an Archean stratovolcano within the Uchi Greenstone belt of Canada. They conclude most of the initial volcanic activity was quiet, producing a flat, widespread basaltic cone. Subsequent to this, vigorous explosive activity generated a fragmental volcanic pile on the basaltic platform. The change in eruptive mode is considered to be due to an increase in gas pressure (pO_2) of the original magma, allied to an increase in viscosity.

Heavy mineral analyses

A total of five samples from the present area of study were selected for heavy mineral analyses. The analyses were done out of curiosity but may be useful if a heavy mineral study of the eastern Vermilion district is done in the future. One sample was taken from each of the three structural segments (Knife Lake greenstone, Spoon Lake, and Kekekabic Lake) for analysis in addition to a porphyritic syenodiorite sample and a porphyritic hornblende andesite sample.

Each of the samples analyzed was mechanically crushed to a fine sand. The samples were then washed and dried overnight. Subsequent sieving was done on a vibrating shaker using a 250 micron sieve. Sieved samples were put in heavy liquid (tetra-bromoethane) and allowed to settle 45 minutes. The heavy minerals collected after settling were washed with acetone, hand split, and mounted on thin section slides. During petrographic study 300 grains were counted, where possible, per grain mount.

Knife Lake greenstone segment

The sample used for heavy mineral analyses was collected from the NE1/4, NW1/4, NE1/4, of Sec. 27, T. 65N., R. 7W. Only 90 grains were counted in this sample. The heavy minerals found in the grain mount included 41% pyrite, 24% magnetite, 19% hematite, 7% zircon, 5% leucoxene, and 4% apatite. The heavy minerals are all angular except for one subrounded zircon grain, one rounded magnetite grain, and one rounded hematite grain. The zircon grains studied are pale pink (one polar), minute prisms with pyramidal terminations. They have high relief, parallel extinction, and third order birefrigence.

Spoon Lake segment

The one sample studied from this segment was collected from the SW1/4, SE1/4, NW1/4, of Sec. 26, T. 65N., R. 7W. It contains 98% pyrite, 1% apatite, 0.6% zircon, and 0.4% hornblende. The pyrite cubes are light yellow in color and have characteristic striations on the cleavage surfaces. All the heavy minerals in this slide are angular.

Kekekabic Lake segment

The heavy mineral slide studied from this segment consisted, not surprisingly, of 100% hornblende grains. The sample was collected from the NW1/4, SW1/4, SE1/4, of Sec. 29, T. 65N., R. 6W. The hornblende grains are angular, elongate, and have an extinction angle between 13^{o} and 20^{o}. The pleochroic scheme of the grains studied is: alpha=yellow-green; gamma=dark green; and beta=green.

A porphyritic syenodiorite sample studied from the Kekekabic Lake segment contains 86% hornblende, 13% apatite, and 1% sphene. The syenodiorite sample studied was collected from the SW1/4, SW1/4, SW1/4, of Sec. 29, T. 65N., R. 6W.

The red hornblende andesite sample analyzed was collected from the SE1/4, SW1/4, NW1/4, of Sec. 29, T. 65N., R. 6W. It contains 100% hornblende grains which have the same shape, characteristic extinction angle, and pleochroism described earlier.

X-ray analyses

Two slate samples were selected from the present area of study for x-ray analyses. The samples selected were too fine-grained to yield any petrographic information under the microscope. Therefore, x-ray analyses was used to determine the minerals present in the samples. One of the samples analyzed was collected from the Spoon Lake segment (NE1/4, SW1/4, NW1/4, Sec. 35, T. 65N., R. 7W.) where it is interbedded with predominantly mafic tuff beds. The other sample was collected from the Kekekabic Lake segment (NE1/4, NE1/4, NW1/4, Sec. 36, T. 65N., R. 7W.) where it is interbedded with tuff and agglomerate. Radiation for the analyses was provided by a Cu tube that emits K-alpha radiation. The samples were scanned through a 2θ angle of 34^{o} (6^{o} - 40^{o}).

Both of the samples were prepared for x-ray analyses by hand crushing a rock fragment from each sample to a fine powder. The powder was mixed with water on a glass slide and left to dry. The sample was then placed in the x-ray machine and analyzed.

The two slate samples analyzed have identical mineralogies. They both contain, in order of decreasing significance, orthoclase, low albite, chlorite, actinolite, ilmenite, epidote, albite, and quartz (found in only one sample).

PROVENANCE and SEDIMENTATION

Provenance

Graywackes within the present area of study are volcanogenic, derived predominantly from volcanic rocks. Plutonic source rocks also existed during Knife Lake time (Ojakangas, 1972a, 1972b; McLimans, 1971, 1972; and Severson, 1978) but contributed little framework material to the graywackes of the Kekekabic Lake area. A mixed provenance of volcanic and plutonic rocks is typical of continental orogenic belts or island arc systems (Anhaeusser and others, 1969).

A total of 17 lithic graywacke samples from the Kekekabic Lake area was used for petrographic study. Volcanic rock fragments comprise from 13 to 57 percent of the rocks, plagioclase from 8 to 17 percent, volcanic quartz from zero to 2 percent, common undulose quartz from zero to 11 percent, and polycrystalline quartz from zero to 1 percent. Hornblende varies from zero percent in some lithic graywacke samples to 71 percent in hornblende-rich lithic graywacke samples that may be tuffaceous. A matrix of chlorite, epidote, sericite, and smaller framework grains and rock fragments constitutes from 0.3 to 60 percent.

The volcanic rock fragments found in all the lithic graywacke samples studied are, in order of decreasing abundance, andesite, dacite, basalt, rhyolite, and recrystallized (latite to trachyandesite) tuff fragments. Andesite fragments may comprise from zero to 15 percent of a rock, dacite from zero to 17 percent, basalt from zero to 26 percent, rhyolite from zero to 7 percent, and recrystallized tuff fragments from zero to 14 percent. In addition, hornblende andesite and hornblende trachyte-latite-trachyandesite are found locally in the Kekekabic Lake segment. The volcanic rock fragments would seem to typify erosion of a calc-alkaline volcanic pile, particularly the middle (andesite to dacite) portion. The volcanic rock fragments were presumably eroded from subaqueous to subaerial porphyritic flows, hypabyssal rocks, and pyroclastic (tuff) deposits. Formation of a typical Archean volcanic pile has been modeled, for example, by Goodwin (1968) and Clifford and McNutt (1971).

Siltstone rock fragments are distributed throughout the area, comprise a minor portion (3 percent) of all the rock fragments studied, and may constitute from zero to 28 percent of a lithic graywacke sample. They apparently represent erosion of muddy sediments by turbidity currents within a basin of moderate depth.

Plutonic rock fragments are found locally in the Kekekabic Lake segment and consist of quartz-plagioclase aggregates. Though volumetrically insignificant in the present area of study (the maximum amount present in any one thin section is 3 percent), plutonic detritus, particularly conglomerate clasts, become more abundant to the northeast towards the Saganaga Tonalite (McLimans, 1971, 1972). Plutonic rock fragments consisting of quartz and K-feldspar have been studied in graywacke samples from the eastern Vermilion district by Ojakangas (1972a, 1972b) and Severson (1978), and attributed to certain phases of the Saganaga Tonalite. Such K-feldspar-bearing plutonic fragments are apparently not present in the Kekekabic Lake area; at least, none were recognized in the lithic graywackes studied. The quartz-plagioclase aggregates, however, resemble Saganaga Tonalite and presumably were also derived from this batholith. Green (1970) has noted other "granitic" pebbles, which are not of the Saganaga type, in minor conglomerate lenses of the Knife Lake Group in the central Vermilion district. He suggested that the granitic pebbles may represent material derived from either an original granitic crust, or a small now unexposed pluton. Plutonic rock fragments other than the Saganaga type were not recognized in this study, nor in the above-mentioned studies by McLimans, Ojakangas and Severson.

The lithic graywackes of the Kekekabic Lake segment are rich in hornblende compared to those of the Spoon Lake segment. A few framework grains of hornblende resemble hornblende phenocrysts seen in porphyritic volcanic rock fragments and may have been derived from subaqueous to subaerial porphyritic flows. However, the majority of the hornblende grains found in the lithic, as well as the feldspathic, graywackes resemble, and apparently were derived from hornblende-rich tuffaceous sediments deposited prior to a major episode of extrusion (hornblende andesite) and explosive volcanism (hornblende tuff and agglomerate). The evidence for this includes the observation that graywackes which lie beneath the tuff and agglomerate show a stratigraphic increase in hornblende content as the contact with the tuff and agglomerate is approached.

A total of 13 feldspathic graywacke samples was studied petrographically. Plagioclase comprises from 5 to 48 percent of the rock, volcanic quartz from zero to 1 percent, common undulose quartz from 2 to 19 percent, polycrystalline quartz from zero to 2 percent, hornblende from zero to 14 percent, K-feldspar from zero to 14 percent, and rock fragments (predominantly dacite and andesite) from 1 to 28 percent. A matrix similar to that described for the lithic graywackes constitutes from zero to 62 percent.

Comparison of framework plagioclase grains with mafic (basalt or andesite) tuff samples indicates most of the plagioclase was derived from mafic tuffaceous sediments deposited on the unstable slopes of a volcanic pile. Plagioclase is also abundant in the groundmass of basalt, andesite, and dacite volcanic rock fragments. This might indicate some of the framework grains of plagioclase have been derived from mafic to intermediate flows or hypabyssal rocks. However, the plagioclase observed in the groundmass of these volcanic rock fragments is generally finer-grained than the plagioclase observed in the feldspathic graywackes. Therefore, mafic to intermediate flows and intrusive rocks were probably not a significant source for the feldspathic graywackes. Plagioclase grains may have also been derived from the Saganaga Tonalite since plutonic rock fragments consisting of quartz and plagioclase are found in the graywackes of the present study. In some cases, the framework plagioclase grains do resemble the plagioclase seen in the plutonic rock fragments. However, the plutonic rock fragments are volumetrically insignificant relative to the volcanic rock fragments in the graywackes studied. Therefore, the Saganaga batholith is herein not considered to be a significant source for detrital plagioclase grains.

Framework grains of K-feldspar have been noted in graywackes of the eastern Vermilion district by Ojakangas (1972a, 1972b) and Severson (1978). Ojakangas concluded most of the K-feldspar grains in the graywackes of the eastern Vermilion district were derived from the Saganaga Tonalite since: 1) some plutonic fragments of his study consisted of quartz, plagioclase, and K-feldspar; and 2) the Saganaga Tonalite contains approximately 15 percent K-feldspar (McLimans, 1971, 1972) in certain phases. As previously mentioned, plutonic fragments consisting of quartz and K-feldspar were not recognized in the graywackes of the present study. Hence, it is doubtful that the Saganaga Tonalite was a source for the detrital K-feldspar grains found in the feldspathic graywackes.

K-feldspar is found in the groundmass and as phenocrysts in rhyolite volcanic rock fragments, indicating some of the framework grains of K-feldspar may have been derived from felsic subaqueous to subaerial flows. However, more significant is the fact that one trachyte to latite crystal tuff sample was collected from the Kekekabic Lake segment. Comparison of framework K-feldspar grains and K-feldspar tuff crystals indicates the majority of K-feldspar in the feldspathic, as well as lithic, graywackes is probably tuffaceous in origin.

Mafic (basalt or andesite) and felsic (trachyte to latite) crystal tuffs are locally interbedded with the graywackes and slates of the present study area. The tuffs apparently represent pyroclastic debris that was blown out of volcanic vents and deposited either directly into a subsiding basin or onto the unstable slopes of a volcanic pile. Bed-by-bed descriptions done on relatively clean unweathered outcrops which expose several meters of section indicate nearly three-fourths of the tuff beds studied in one outcrop (after petrographic study had revealed several of the beds to be tuffs) are graded. In contrast, only one-third of the graywacke beds studied in two outcrops and assumed to be deposited by turbidity currents (Ojakangas, 1972a, 1972b), are graded. Therefore, it is assumed, tacitly, that the mafic and felsic tuffs were deposited directly into a subsiding basin rather than being transported by turbidity currents. Spasmodic tuff deposition was followed by renewed deposition of lithic and feldspathic graywackes. However, within the present area of study, explosive volcanism may have been contemporaneous with graywacke deposition to some extent since: 1) the crystal tuffs appear to be gradational vertically, into feldspathic graywackes; and 2) detrital hornblende, plagioclase, and K-feldspar grains in both the lithic and feldspathic graywackes apparently are tuffaceous in origin.

Three arkose samples were studied petrographically. Common undulose quartz comprises from 8 to 12 percent of the rock, volcanic quartz from zero to 1 percent, plagioclase from 22 to 28 percent, and rock fragments (mostly mud chips, some dacite) from zero to 10 percent. A matrix consisting of a granular mixture of quartz and plagioclase constitutes from 22 to 48 percent.

Arkose sandstones imply erosion of a feldspar-rich source area. This source is characteristically a granite pluton or gneiss since arkoses are typically composed of K-feldspar (Pettijohn and others, 1972). Arkose within the present area of study, however, is composed entirely of plagioclase (albite-oligoclase). The Saganaga batholith would be a likely source for the arkoses since it has a close proximity to the study area, was uplifted and rapidly unroofed during Knife Lake time, and has a tonalitic composition which is plagioclase-rich. However, as has been discussed earlier, the Saganaga batholith was not a significant source for the framework material studied in the present area. Lithic and feldspathic graywackes of the present study are composed almost exclusively of volcanic material derived from mafic to intermediate porphyritic flows, hypabyssal rocks, and mafic to felsic crystal tuffs. In addition, if the arkose was derived from the Saganaga it should contain some detrital K-feldspar grains since some phases of the Saganaga Tonalite contain approximately 15 percent K-feldspar. It seems unlikely that K-feldspar would be selectively winnowed or weathered out before plagioclase, leaving an arkosic sediment rich in plagioclase. However, the lack of K-feldspar within the arkose may mark a time during which only K-feldspar--poor phases of the Saganaga were exposed.

Detrital framework grains of feldspar (both plagioclase and K-feldspar) contained in the graywackes of the present study are, for the most part, volcanic in origin, having been derived predominantly from mafic to felsic crystal tuffs. Therefore, the arkose was probably formed by the erosion of a thick sequence of mafic (basalt or andesite) tuffs, deposited on the flanks of a developing volcanic center, and comprising a major portion of a volcanic pile accumulation. Deposition and subsequent erosion of plagioclase-rich mafic to intermediate subaqueous and subaerial flows and hypabyssal rocks may have also supplied detritus for arkose formation. However, as mentioned previously, they are not herein considered to be a significant source for the arkose since the plagioclases within the flows and intrusives are finer-grained than the detrital plagioclases. According to Pettijohn and others (1972), arkose formation is assumed, tacitly, to be controlled by the rate of erosion, or more specifically the formation of arkose is favored by an area of high relief. Hence, the tuffs and/or flows and hypabyssal rocks probably accumulated to a substantial thickness within the pile which elevated them above the surrounding terrain and allowed them to be selectively eroded.

Arkose and graywacke samples of the present study apparently mark a stage in the denudation of a volcanic pile during which a portion of the fragmental edifice, deposited above the pillowed basalt flows comprising the mafic platform (Goodwin, 1968; Clifford and McNutt, 1971), was eroded.

Polycrystalline quartz grains found in the graywackes of the present study comprise a minor portion of the framework grains studied, resemble Saganaga Tonalite quartz "eyes", and apparently are plutonic in origin. Common undulose quartz resembles volcanic quartz in some cases and therefore some of the common quartz may have originally been volcanic, derived from dacite to rhyolite flows which contained quartz phenocrysts, or from tuffs. However, most of the common undulose quartz is presumably of plutonic origin.

Volcanic quartz grains are probably tuffaceous in origin since, as phenocrysts, they would probably be difficult to free from porphyritic volcanic rocks without extensive weathering (Ojakangas, 1972a, 1972b).

Iron-formation occurs in some outcrops within the Kekekabic Lake area as thin bands of ferruginous slates that are sporadically interbedded with graywackes and green slates. In thin section, the iron-rich bands are concentrations of very fine hematite and larger crystals of magnetite (Stark, 1929; Severson, 1978). Stark referred to these iron-rich bands as the Agawa iron-formation and concluded the iron-formation was associated with iron-rich andesite tuffs that were deposited in water. Subsequent agitation of the water by explosive volcanic ejections served to mechanically concentrate the detrital iron particles into bands. Stark stated that chemical precipitation was not a factor in concentrating the iron-rich particles. Only one thin section of iron-formation from the Kekekabic Lake area was studied petrographically. The iron-rich bands are separated by graded plagioclase-rich tuffaceous layers presumably deposited directly into water. The euhedral hematite and magnetite cubes comprising the iron-rich bands are herein considered to reflect crystal growth subsequent to chemical sedimentation. Lower Precambrian banded iron-formations associated with volcanic rocks have been attributed to exhalative volcanic processes (Goodwin, 1962).

Sedimentation

Outcrops within the present area of study are dominated by a monotonous succession of graywacke and slate. Interbedded with the graywacke and slate in some outcrops are conglomerate, tuff, and iron-formation. The graywackes and slates comprise a thick (2000 feet) sedimentary sequence that overlies arkose and underlies porphyritic hornblende andesite and tuff and agglomerate.

In outcrop, the graywacke and slate beds are well defined, appear flat based, and are regularly bedded. Outcrops which expose several meters of section show the beds to have good lateral continuity; chaotic slump-type deposits caused by downslope mass movements are noticeably absent. Graded bedding is the most apparent sedimentary feature seen in the graywacke-slate outcrops. The predominant grading is from medium- (0.5 to 1.0 mm) to fine-grained ($<$0.5 mm). Although some of the grading seen in outcrop probably resulted from the settling of pyroclastic (tuffaceous) debris into a subsiding basin, the majority is herein considered to be the result of turbidity currents. Ojakangas (1972a, 1972b) has concluded turbidity currents were instrumental in graywacke deposition throughout the eastern Vermilion district.

Ripple marks or medium- to large-scale cross-beds, indicative of shallow agitated water, were not seen in the graywacke-slate outcrops studied. In addition, rock fragments within the lithic graywackes studied are all angular, indicating the sediments have not been reworked. Therefore, the graywackes may have been deposited in a moderate to deep water basin. Severson (1978) also noted the lack of shallow water sedimentary features in the graywackes of his study and concluded they were deposited in deep water. Small scale (6-10 cm thick), low angle cross-beds, however, are seen in tuff and agglomerate outcrops of the Kekekabic Lake segment, as is trough cross-bedding (found in only one outcrop). According to Matthews (1974), low angle cross-bedding occurs in meandering stream and intertidal beach environments. The combination of trough and small scale, low angle cross-bedding is herein considered to indicate fluvial transport of tuffaceous sediments, possibly by meandering streams, from the flanks of a volcanic center into a basin. A cross-stratified pyroclastic unit has been studied in the Abitibi greenstone belt of Canada by Hyde and Walker (1977). They concluded the cross-stratification was formed by aqueous reworking of tuff particles, most likely by fluvial processes. Deposition of the underlying arkose, graywackes, slates, tuffs, and iron-formation may have partially filled the initial moderate to deep water basin prior to: 1) extrusion of the porphyritic hornblende andesite which was followed by; 2) deposition of the hornblende-rich tuff and agglomerate.

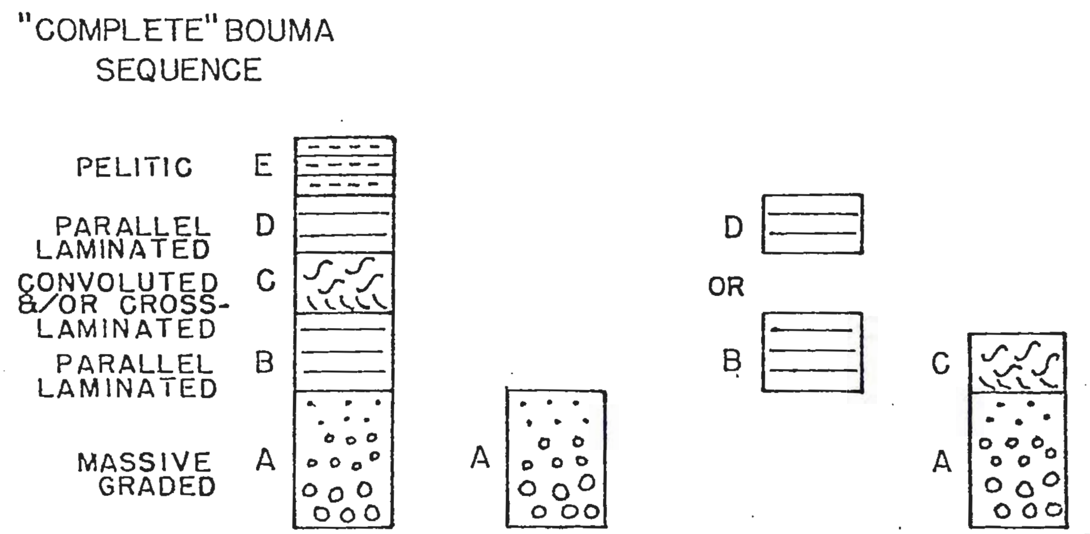
The graywacke detritus probably originated as temporary accumulations on the slopes of volcanic basalt-andesite-rhyolite piles. These accumulations were periodically jarred loose by slumping which was triggered by earthquakes, volcanic eruptions, or storm waves causing submarine landslides, most of which developed into turbidity currents (Ojakangas, 1972a, 1972b). The currents presumably flowed into a subsiding basin as indicated by the great thickness of volcanic and sedimentary rocks within the eastern Vermilion district (Gruner, 1941).

Lithic graywackes are herein assumed to indicate erosion of flows and hypabyssal rocks which were probably buried during short-lived periods of explosive volcanism and reexposed after the tuffaceous material had been redeposited by turbidity currents as feldspathic graywackes. Slates represent the background sediment of the basin which was deposited over a long period of time. Each mud interbed may be the result of hundreds or thousands of years of slow accumulation (Ojakangas, 1972a). Slate deposition was repeatedly interrupted by the arrival of short-lived turbidity currents. Mafic to felsic crystal tuffs indicate periodic volcanic activity during which pyroclastic material settled directly into the basin. Tuff deposition may have been contemporaneous with the formation of lithic and feldspathic graywackes since nearly all the detrital framework grains in the graywackes studied are volcanogenic.

Deposition of sedimentary and volcanic rocks proceeded in this manner throughout Knife Lake time as evidenced by the lack of unconformities between members.

The slope of the basin was relatively steep since Saganaga Tonalite clasts, up to 15 cm in diameter, have been transported to Ensign Lake, some 24 miles from the source area (McLimans, 1971, 1972). The presence of a few conglomerate interbeds within the graywackes and slates of the present study indicate transportation to the unstable basin slope may have been by high-velocity streams.

Bouma (1962) has described a "complete" turbidite bed composed of five internal units (A-B-C-D, and E, Fig. 56). Within the present study area, the graywacke sequences consist predomi-



Measured Section I (105 beds)	Graded	24%		6%
	Not Graded	70%		
Measured Section II (25 beds)	Graded	76%	1%	
	Not Graded	23%		
Measured Section III (7 beds)	Graded	22%		
	Not Graded	78%		

Figure 56: Summary of Bouma sequences found in graywacke beds of the present study

nantly of the top-truncated A unit. "Complete" sequences are not found but sequences with A-C-E or B-D-E missing are also present. Composite beds composed of 3 to 4 thin (1 to 5 cm) graded units in juxtaposition without intervening slate layers are present in two of the three measured sections studied (Table 11). Bed-by-bed descriptions were done on three relatively clean, unweathered outcrops which exposed several meters of section. A bed-by-bed description was done in each of the structural segments except the Knife Lake greenstone segment where no suitable outcrop existed.

Most of the features of turbidites can be explained by a combination of erosion at the head of a turbidity current and deposition from the body and tail of the current (Middleton and Hampton, 1973). Erosion of preceding turbidite beds would account for the composite A units and Bouma sequences where the top units are missing. An absence of top units may also be explained by a lack of deposition within the turbidity current, such that the coarse material was deposited nearer the source and the rest of the turbidity current deposited the upper units farther from the source. "Complete" sequences or sequences with missing lower units, would be deposited from the body and tail of the current as a function of flow regime. The units of the sequence representing from bottom to top, successively lower flow regimes (Walker, 1967). Major factors in determining the flow regime would be the distance traveled and the initial velocity and the sediment load of the current. Walker (1967) also suggested that the turbidites can be classed as either "proximal" or "distal" depending on the order of Bouma units. A Bouma A-A-A sequence would be proximal whereas sequences

TABLE 11--THREE MEASURED SECTIONS IN PRESENT STUDY AREA

	Measured Sections		
	I	II	III
Thickness:	39.0m	7.0m	13.2m
Number of beds:	155	43	65
Conglomerate beds:			
Percent of total thickness	4		
Average bed thickness	40cm		
Range of bed thickness	2-154cm		
Number and percent of total	4-3		
Graywacke beds:			
Percent of total thickness	64	61[a]	5[b]
Average bed thickness	24cm	17.2cm	2cm
Range of bed thickness	0.2-140cm	0.5-297cm	0.1-25cm
Number and percent of total	105-67	25-58	31-48
Number and percent graded	32-30	19-76	7-22
Percent with convolutions	6	0	0
Percent composite beds	11	12	0
Alternating siltstone and slate beds:			
Percent of total thickness	32	39	95
Average bed thickness	27cm	15cm	38cm
Range of bed thickness	0.5-310cm	0.5-90cm	0.1-585cm
Number and percent of total	46-30	18-42	33-51

I NW1/4, SE1/4, Sec. 24, T. 65N, R. 7W. (Spoon Lake Segment)

II NE1/4, SW1/4, NW1/4, Sec. 25, T. 65N, R. 7W. (Spoon Lake Segment)

III NW1/4, SW1/4, NE1/4, Sec. 32, T. 65N, R. 6W. (Kekekabic Lake Segment)

(a) Predominantly water laid mafic tuff
(b) Possibly includes some water laid felsic tuff beds

beginning with unit B or C would be distal. Indicators of distal (distant) deposition, as opposed to proximal (nearby) deposition, also include: thinner beds; finer-grained beds; parallel-sided, regular beds; well-developed mudstone layers between graywacke beds; well-graded beds; beds with sharp bases (a marked contrast in grain size compared to underlying fine-grained beds) and tops which grade into fine sediment; and a lack of scours, channels, and composite beds (Walker, 1967).

The graywacke beds contained in the three measured sections of this study (Table 11) generally have the attributes of deposition in a distal environment, although the presence of some conglomerate beds and some composite beds within the Spoon Lake segment may be suggestive of more proximal deposition in this segment. Walker and Mutti (1973) have described several turbidite facies and facies associations which allow generalizations to be made as to where a particular turbidite sequence may occur in a turbidite basin. Using the facies associations outlined by Walker and Mutti, the turbidite sequences of the Spoon Lake segment (Fig. 56 and Table 11) correspond to facies within the submarine fan of a slope-fan-basin floor system of a turbidite basin (Fig. 57). In particular, the turbidites of this segment are contained in the depositional lobe of the middle portion of the submarine fan. The one bed-by-bed description done in the Kekekabic Lake segment consists almost entirely (95 percent) of muddy interbeds. Thin (2 cm), non-graded, graywacke beds comprise only 5 percent of the outcrop. This outcrop lies just outside of Severson's (1978) thesis area which extended from the Kekekabic Ponds to the Saganaga Tonalite

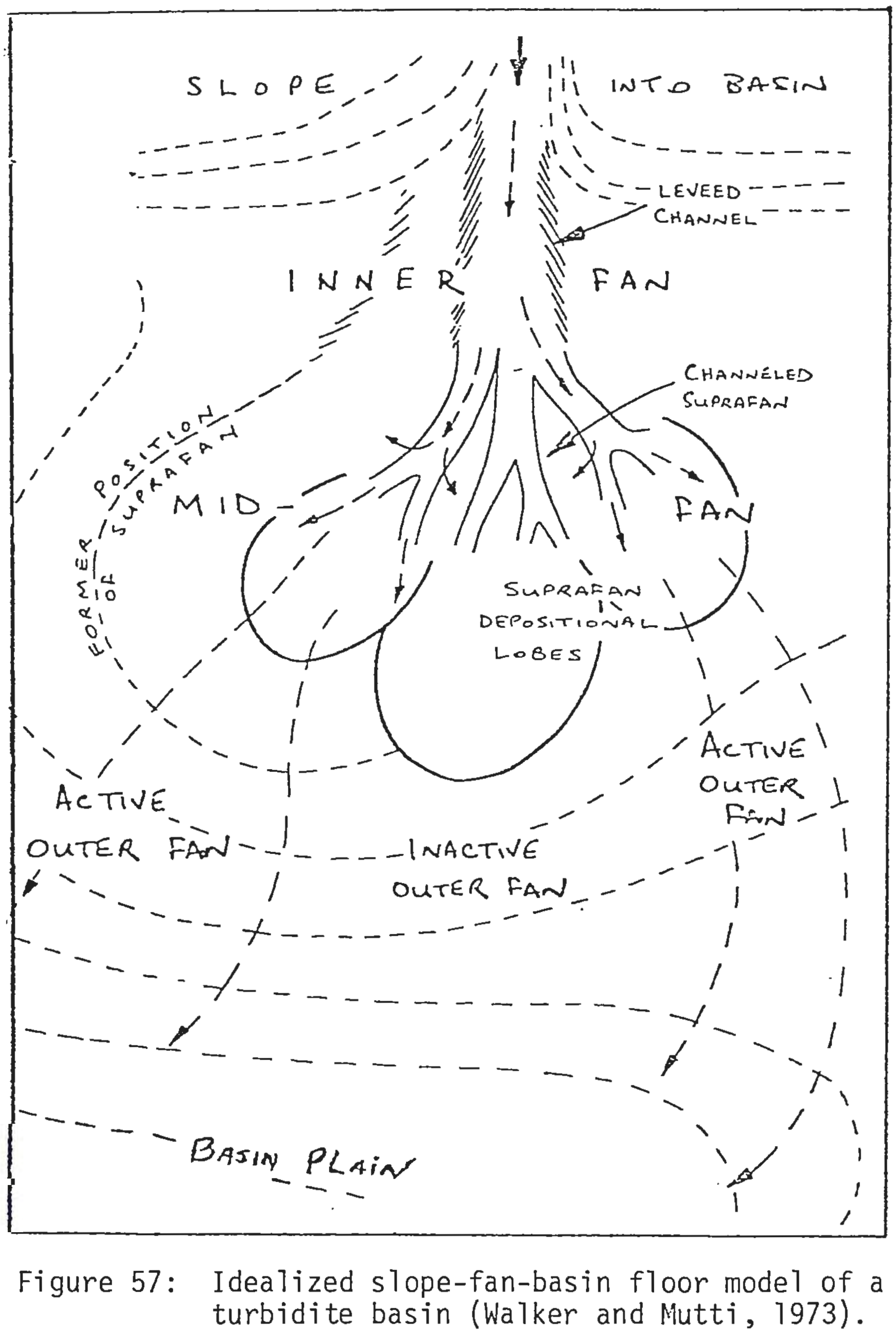


Figure 57: Idealized slope-fan-basin floor model of a turbidite basin (Walker and Mutti, 1973). Turbidite sequences of present study correspond, in general, to facies associated with a depositional lobe within the mid-fan.

at the northeast end of the eastern Vermilion district. Severson concluded the proximal turbidites (mid-fan, Fig. 57) within the Kekekabic Lake segment are located in the vicinity of Alpine Lake where they abut against the Saganaga Tonalite. Here the graywackes consist of very coarse-grained A-B sequences. To the southwest along strike, B-C-D, B-C, C-D, and C sequences become more common and indicate a more distal (suprafan) environment. The abundant muddy interbeds found in the measured section of this study may correspond to the pelagic and hemipelagic facies deposited on the inactive outer fan (Fig. 57) or basin plain. The associated graywacke beds apparently represent the distal portion of short-lived turbidity currents. Hence, turbidite sequences of the Kekekabic Lake segment record transport of sediment by turbidity currents within a turbidite basin from the northeast to the southwest. The sequences preserved are comparable with facies associations of a submarine fan as described by Walker and Mutti (1973).

The southwestward transport of sediment in the Kekekabic Lake segment away from the Saganaga Tonalite, as indicated by turbidite sequences, also coincides with the southwestward decrease in the size and abundance of Saganaga Tonalite clasts described by McLimans (1971, 1972).

Miscellaneous sedimentary features such as flame structures and mud chips were observed in outcrop. Flame structures are indicative of soft sediment deformation, primarily due to compaction, while mud chips apparently are the result of erosion of underlying muddy beds by turbidity currents. Both of these sedimentary features fit the turbidite model proposed by Middleton and Hampton

(1973).

As previously mentioned, small scale, low angle cross-beds and a larger (24 cm thick) trough cross-bed were found in tuff and agglomerate outcrops of the Kekekabic Lake segment. In addition, one small scale, high angle cross-bed was seen in a graywacke-slate outcrop. A total of ten paleocurrent measurements, all that were available, were taken at nine locations, shown in Figure 58. These measurements were rotated to the horizontal, with the plunge (determined by cleavage-bedding intersections) taken out, and plotted on the rose diagram shown in Figure 58. The nine paleocurrent directions measured in the tuff and agglomerate show a unimodal pattern which may indicate fluvial or deltaic transport of sediments, primarily to the northwest (Pettijohn and others, 1972). However, the rose diagram may be slightly misleading since only two fewer paleocurrent measurements to the northwest would have resulted in a more bimodal pattern characteristic of tidally influenced sediments. The small scale and low angle of the cross-beds seen in the tuff and agglomerate has been discussed earlier as indicating a shallow, meandering stream environment (Matthews, 1974). The unimodal pattern seen in the rose diagram is herein considered to reflect a primary transport direction from southeast to northwest.

The one trough cross-bed studied indicates a direction of fluvial transport towards the northeast. Similarly, the one paleocurrent measurement taken from a graywacke-slate outcrop at the east end of Kekekabic Lake (Fig. 58) also indicates sediment transport towards the northeast. As discussed earlier, the turbidites

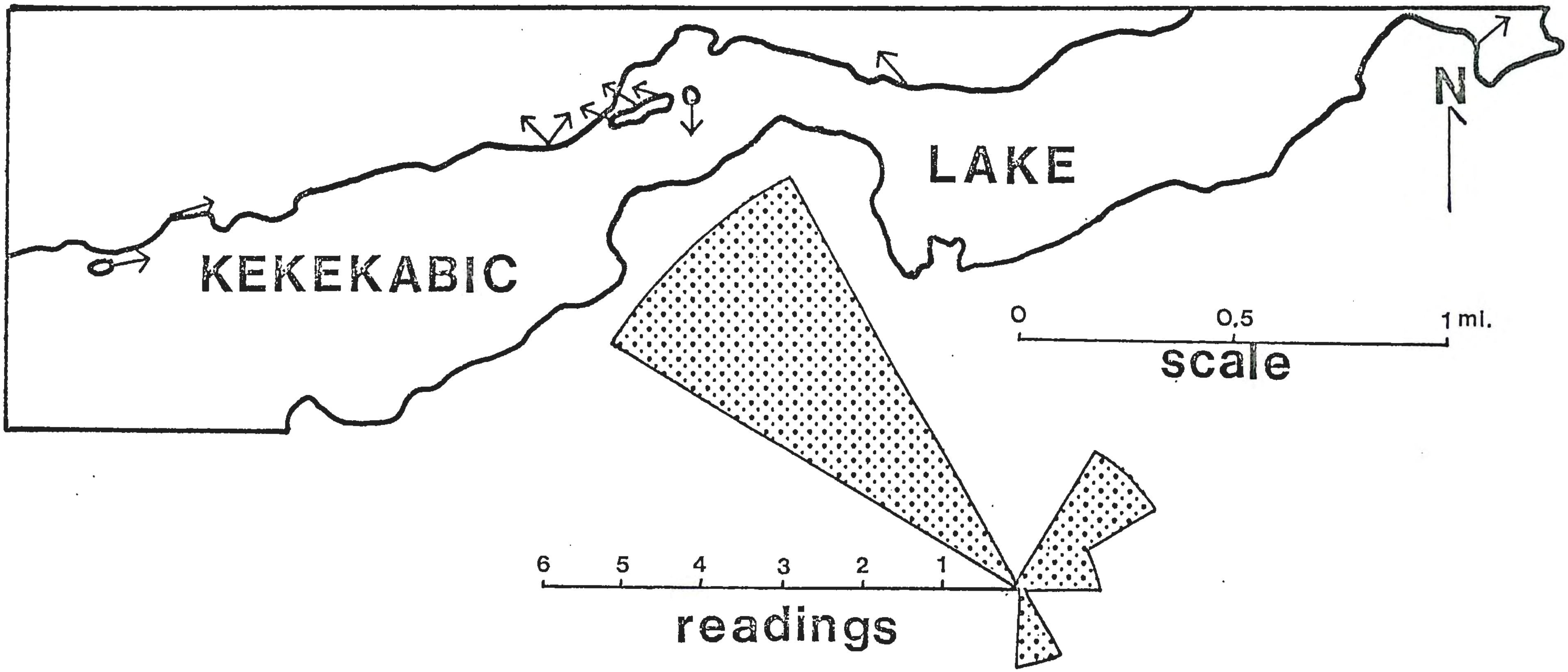


Figure 58: Location and direction of each of the ten paleocurrent measurements taken during present study (small arrows). Rose diagram summarizes paleocurrent directions.

within the Kekekabic Lake segment indicate sediment transport was to the southwest, away from the Saganaga Tonalite. Therefore, the one paleocurrent measurement taken from the graywacke-slate outcrop may reflect minor topographic control.

STRUCTURE

General statement

Rocks within the Vermilion district of northeastern Minnesota were structurally deformed during and subsequent to emplacement of the Vermilion granite-migmatite massif to the north and the Giants Range batholith to the south (Sims, 1972). Two periods of regional folding have been recognized in both the eastern and western parts of the district as has an episode of major longitudinal faulting (Sims, 1972).

In the younger sequences of the Knife Lake Group of the eastern Vermilion district, hinge surfaces of the major isoclinal folds trend east to northeast with near vertical dips and gentle plunges (Gruner, 1941). In addition, post-Algoman longitudinal faulting has divided the eastern part of the district into discrete segments.

In the present area of study at least two periods of folding have been recognized in addition to longitudinal and transverse faulting. Although the rocks of the present study are structurally complex, deformation was not severe enough to erase primary topping directions in graded graywacke beds which made interpretation of the structure possible.

Continuous structures

Bedding planes

Bedding planes within the present area of study are commonly defined by the difference in grain size between graded graywacke bases (Bouma A) and underlying muddy interbeds. Bedding planes of the present study are folded, trend dominantly S 45^{o}-50^{o}W, and have steep dips (60^{o}-90^{o}) predominantly to the southeast. Topping directions within graded graywacke beds indicate bedding planes of the present area are generally linear, but become S-shaped in a few localities along the north shore of Kekekabic Lake, the south shore of Eddy Lake, and the south shore of Knife Lake (Plate 1). Bedding plane measurements were taken predominantly along the shorelines of all the lakes within the area. Few outcrops within the central inland area were suitable for bedding plane measurements. Bedding planes of this study are herein designated as S_1.

Major folds

Kekekabic Lake structural block

Topping directions within graded graywacke beds indicate a syncline makes up the entire Kekekabic Lake structural block (Plate 1). The syncline has a strike length of 4.5 miles and a wavelength of one mile. The amplitude of the syncline was not determined in this study, but Gruner (1941) estimated some isoclinal folds within the eastern Vermilion district may extend to a depth of one mile.

The axis of the syncline, as determined by bedding measurements (Fig. 59), trends S 50^{o}W and plunges 30^{o}. Geologic cross-sections across the Kekekabic Lake structural block (Plate 2 and Fig. 30) indicate the syncline is open with an interlimb angle of approximately 45^{o}.

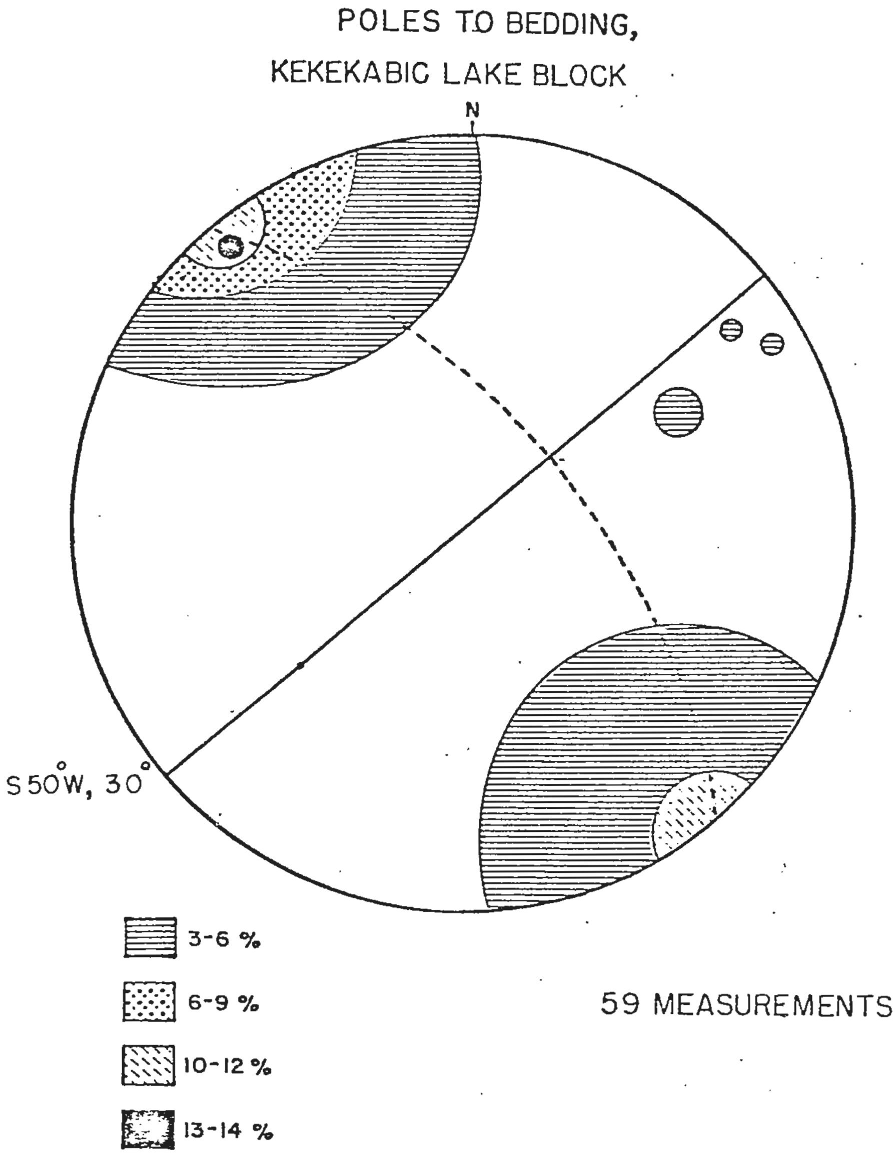


Figure 59: Lower hemisphere equal area projection of poles to bedding from the Kekekabic Lake structural block. Contours are per 1% area.

Fold closure in the Kekekabic Lake structural block was observed between Eddy Lake and the Kekekabic Ponds (NE1/4, of Sec. 29, and SW corner of Sec. 21, T. 65N., R. 6W.). Detailed recording of strike and dip measurements indicates a smooth progression of dips around the nose of the fold from the overturned southeast limb to the northwest limb.

Spoon Lake structural block

Topping directions within graded graywacke beds indicate a syncline lies in the northern part of the Spoon Lake structural block (Plate 1). The syncline has a strike length of 2.5 miles and a wavelength of 0.5 miles. The amplitude of the syncline was not determined in this study nor by Gruner (1941).

The axis of the syncline, as determined by bedding measurements (Fig. 60), trends S 45^{o}W and plunges 35^{o}. The fold is nearly isoclinal (Plate 2) with an interlimb angle of 10^{o}. The south limb of the syncline is overturned.

Fold closure in the Spoon Lake structural block, as defined by only two topping directions, is observed in the NE1/4, SW1/4, of Sec. 25, T. 65N., R. 7W.

Knife Lake structural block

Rocks within the Knife Lake structural block trend N 74^{o}E and dip 60^{o} to the southeast. No reversals of top or dip directions are seen in this block to indicate the presence of a major fold; however, only nine bedding plane measurements were taken in the Knife Lake structural block.

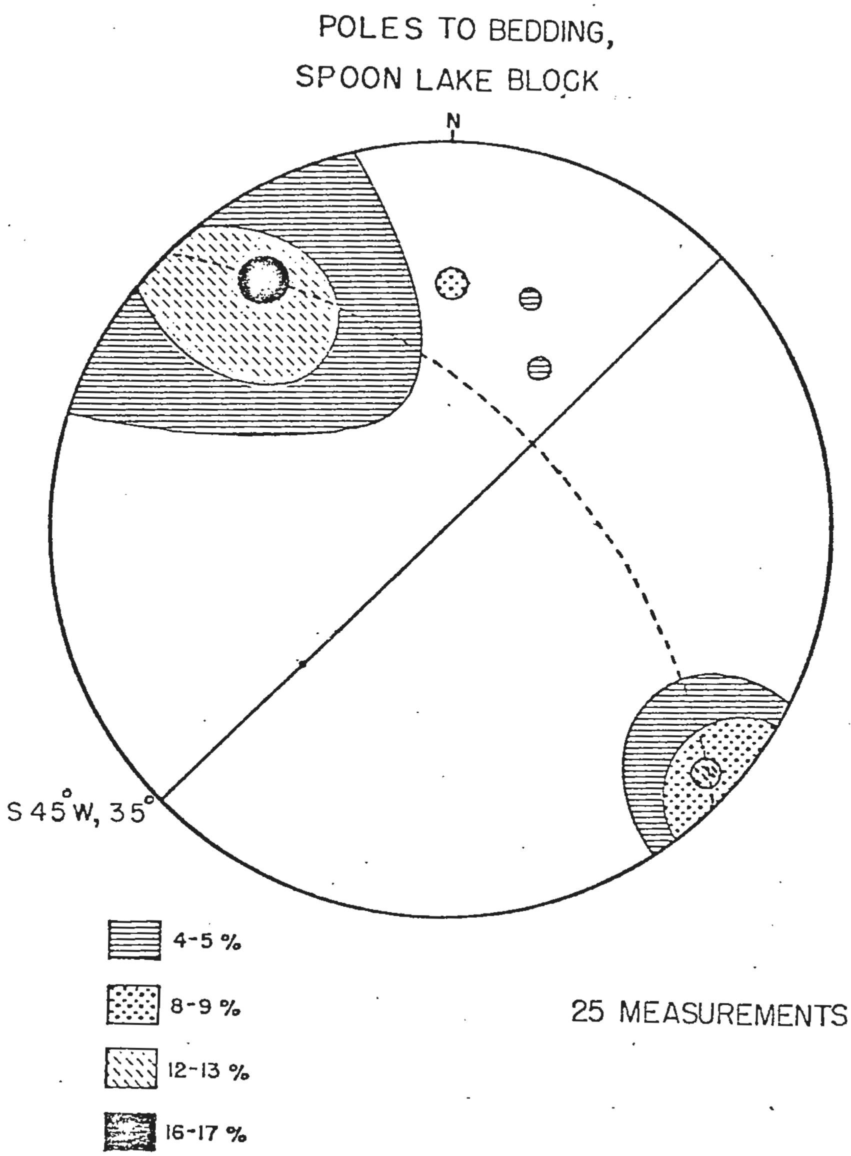


Figure 60: Lower hemisphere equal area projection of poles to bedding from Spoon Lake structural block. Contours are per 1% area.

Minor folds

Kekekabic Lake structural block

A minor, presumably parasitic, fold was observed in the Kekekabic Lake structural block and is located in a small inlet in the SW1/4, NE1/4, NW1/4, of Sec. 35, T. 65N., R. 7W. (Fig. 61).

Figure 61: Parasitic minor fold. SW1/4, NE1/4, NW1/4, Sec. 35, T. 65N., R. 7W.

The minor fold has an amplitude of 0.5 meters and a wavelength of approximately 30 cm. The plunge of the hinge surface was not measured in the field but is nearly horizontal. A convergent dip isogon pattern within this minor fold indicates it is a class 1C flexural slip fold (Hudleston, 1972). The parasitic fold presumably reflects the form of the Kekekabic Lake syncline indicating the syncline may also be a class 1C fold.

A minor "S" fold was observed in this block along the portage between two of the Kekekabic Ponds (SE1/4, NE1/4, SW1/4, Sec. 29, T. 65N., R. 6W.). The S-fold has an amplitude of nearly 2 meters and a wavelength of 1 meter. The plunge of the hinge surface was not measured but is nearly vertical. A divergent dip isogon pattern indicates this minor S-fold is a class 3 fold (Hudleston, 1973). Larger S-folds (amplitudes and wavelengths estimated to be 750 and 1000 feet, respectively), depicted by graded tops in graywacke beds (Plate 1), can be seen along the north shore of Kekekabic Lake (N1/2, of Sec. 31, and the SW corner of Sec. 29, T. 65N., R. 6W. and along the south shore of Eddy Lake (SW corner of Sec. 21, T. 65N., R. 6W.). Cleavage-bedding intersections from the two S-folds located along the north shore of Kekekabic Lake indicate both of these larger S-folds plunge 72° to the southwest.

Spoon Lake structural block

A large S-fold (amplitude and wavelength similar to larger S-folds of the Kekekabic Lake block) is depicted by graded tops in graywacke beds along the south shore of Knife Lake (NE1/4, SW1/4, Sec. 20, T. 65N., R. 6W.). A cleavage-bedding intersection from the fold indicates it plunges 60° to the south-southeast.

S-folds with steeply plunging hinge surfaces apparently reflect a refolding of the rocks contained in the south and north limbs of the Kekekabic Lake syncline and the south limb of the Spoon Lake syncline. In addition, the buckled appearance of the porphyritic hornblende volcanic body, which lies in the Kekekabic Lake syncline (Plate 1), probably also reflects this refolding.

The refolding was apparently pervasive throughout the study area but the lack of good exposures inland obscures its development.

Penetrative minor structures

Cleavage planes were the predominant penetrative structure measured in the field. The cleavage planes are commonly restricted to muddy beds between more sandy graywacke beds. The cleavage planes measured are distinctive in the field because they commonly cut across the muddy beds at a slight angle and do not penetrate the overlying and underlying graywacke beds. In some cases, however, the cleavage is nearly parallel to the muddy beds making the cleavage difficult to distinguish from fine-laminae of siltstone and slate present in some of the muddy beds.

Cleavage planes within the present area of study commonly exhibit a spacing of 1 mm or less, but the spacing can range up to 3 mm. The cleavage planes are presumably slaty cleavage but may actually be fracture cleavage since the amount of micaceous minerals in the muddy beds is not known (Hobbs and others, 1976). Both slaty and fracture cleavage are typical of low-grade metamorphic rocks which includes the majority of the rocks in the eastern Vermilion district (Sims, 1972).

The dominant cleavage trend within the present area of study is N 62^{o}-70^{o}E. This cleavage trend is not parallel to the N 45^{o}-50^{o}E fold axes of the Spoon Lake and Kekekabic Lake synclines, respectively. Therefore the cleavage planes of the present study area are herein assumed to have been produced during a second period of deformation, subsequent to an initial deformation that produced the Spoon Lake and Kekekabic Lake synclines. The cleavage planes are herein designated as S_2.

Kekekabic Lake structural block

A total of 43 cleavage measurements were taken in the Kekekabic Lake structural block (Fig. 62). Cleavages within this block trend dominantly N 62^{o}E and dip 77^{o} to the southeast.

One set of cleavage planes in Figure 61 trends N 38^{o}E and dips 78^{o} to the northwest. These cleavage measurements may be erroneous, but probably indicate some variation away from the dominant cleavage trend of the Kekekabic Lake structural block.

The poles to cleavage shown in Figure 62 reflect cleavage measurements taken predominantly along the north shore of Kekekabic Lake (particularly the east end of the lake), along the eastern shores of the Kekekabic Ponds, and the south shore of Eddy Lake (Plate 1). Inland areas within this structural block yielded few cleavage measurements.

Spoon Lake structural block

A total of 29 cleavage measurements were taken in the Spoon Lake structural block (Fig. 63). The cleavages within this structural block trend dominantly N 70^{o}E and dip 60^{o} to the southeast.

One set of cleavage planes within the Spoon Lake block (Fig. 63) trends N 32^{o}E and dips 70^{o} to the southeast. This cleavage plane is similar in trend to the previously mentioned N 38^{o}E cleavage of the Kekekabic Lake structural block. In addition, another set of cleavage planes found in the Spoon Lake structural block (Fig. 63) trends N 50^{o}E and dips 50^{o} to the southeast. A similar

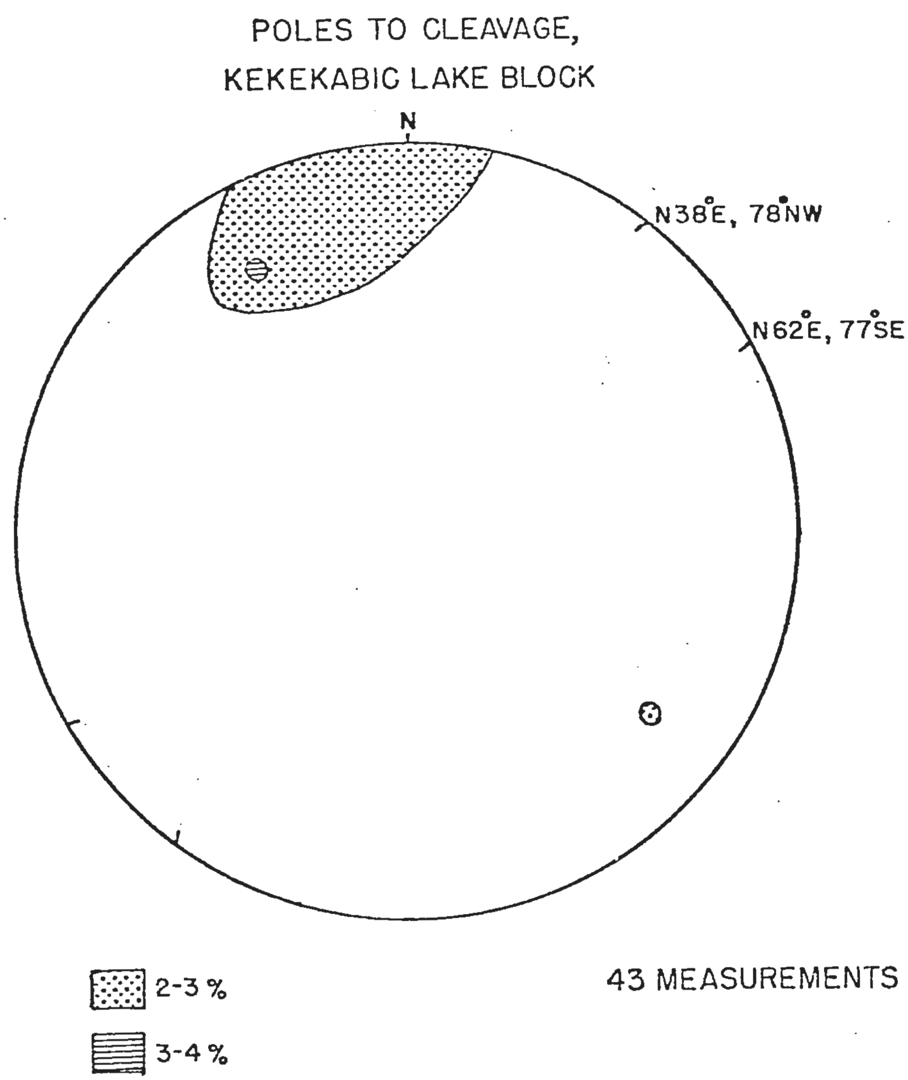


Figure 62: Lower hemisphere equal area projection of poles to cleavage from Kekekabic Lake structural block. Dominant cleavage trend is N 62° E, 77° SE. Contours are per 1% area.

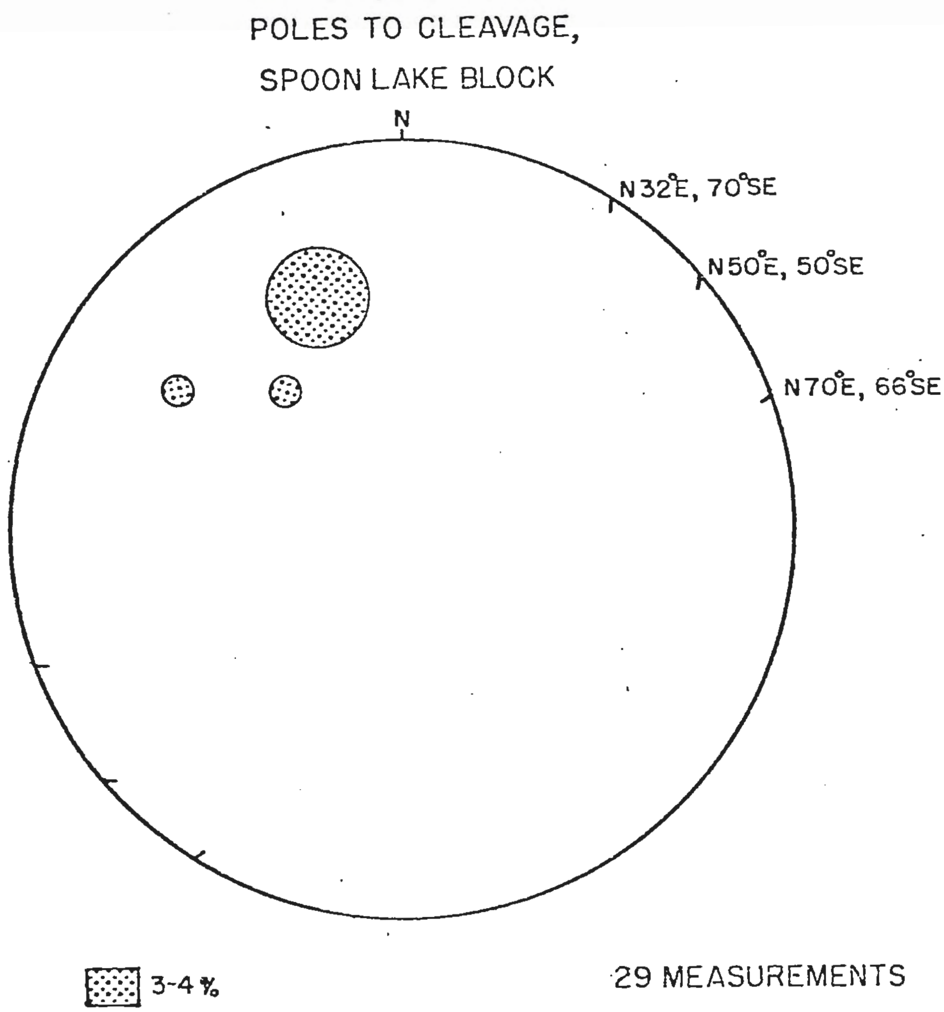


Figure 63: Lower hemisphere equal area projection of poles to cleavage from Spoon Lake structural block. Dominant cleavage trend is N 70° E, 66° SE. Contour is per 1% area.

N 50^{o}E trend is not found in the Kekekabic Lake structural block. The N 32^{o}E and N 50^{o}E cleavages presumably represent incomplete development of cleavages which vary in orientation from the dominant cleavage trend of the Spoon Lake structural block.

The poles to cleavage shown in Figure 63 reflect cleavage measurements taken predominantly along the south shore of Knife Lake and the shoreline surrounding Spoon Lake (Plate 1). Inland areas within the Spoon Lake structural block yielded few cleavage measurements.

Knife Lake structural block

Only five cleavage measurements were taken in the Knife Lake structural block. The cleavages within this structural block trend dominantly N 56^{o}E and dip 69^{o} to the southeast.

Lineations

The only linear features considered in this study are cleavage-bedding intersections. Mineral elongations were not observed in the field, and only a few minor folds were observed in outcrop. The axes of the minor folds were not measured. Cleavage-bedding intersections were not measured directly in the field, but were hand plotted using a stereonet and contoured by computer.

Kekekabic Lake structural block

A total of 18 cleavage-bedding intersections were plotted for the Kekekabic Lake structural block (Fig. 64). The lineations are closely bunched near the center of the diagram; plunging steeply to the southwest, south, and southeast. The bunched

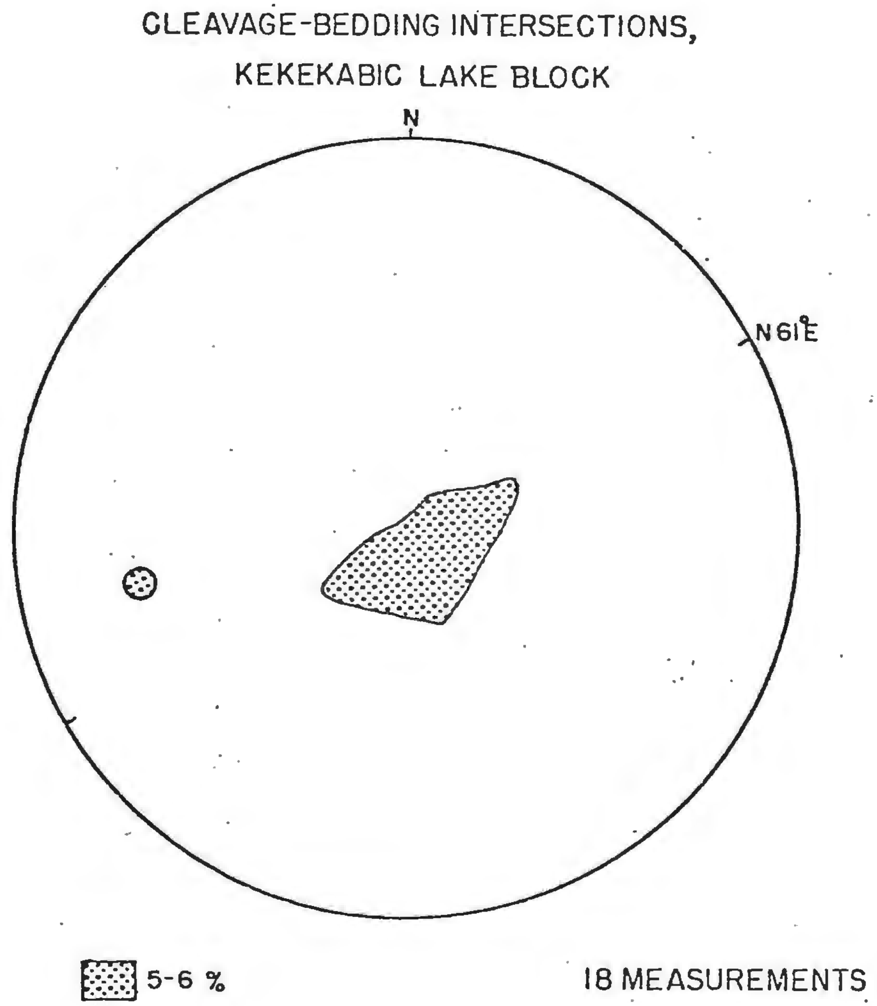


Figure 64: Lower hemisphere equal area projection of lineations (cleavage-bedding intersections) from Kekekabic Lake structural block. Contour is per 1% area.

appearance reflects sampling density since nearly all of the cleavage-bedding measurements were taken near the axis of the Kekekabic Lake syncline, hence, the lineations depict the axis of the fold, but do not really delineate a trend. In fact, the one displaced lineation plunging to the east (Fig. 64) reflects a cleavage-bedding measurement taken directly at the hinge zone of the syncline. There is some extension of the pattern to the southwest and northeast, however, which indicates a trend along a plane whose azimuth is N 61°E and is herein designated as L_2. This trend is parallel to the dominant N 62°E cleavage of the Kekekabic Lake structural block and therefore depicts various orientations of bedding intersecting this plane.

Spoon Lake structural block

A total of 9 cleavage-bedding intersections were plotted for the Spoon Lake structural block (Fig. 65). The lineations within this structural block delineate a trend along a plane whose azimuth is N 75°E and is designated as L_2. This trend is closely parallel to the dominant N 70°E cleavage of the Spoon Lake structural block and therefore depicts various orientations of bedding intersecting this plane. The well-defined great circle trend of the lineations within the Spoon Lake block apparently reflects a more random sampling of bedding orientations in this block.

Knife Lake structural block

Only two cleavage-bedding intersections were plotted for this block. The lineations plunge 68°and 64° to the south and southeast, respectively.

CLEAVAGE-BEDDING INTERSECTIONS,
SPOON LAKE BLOCK

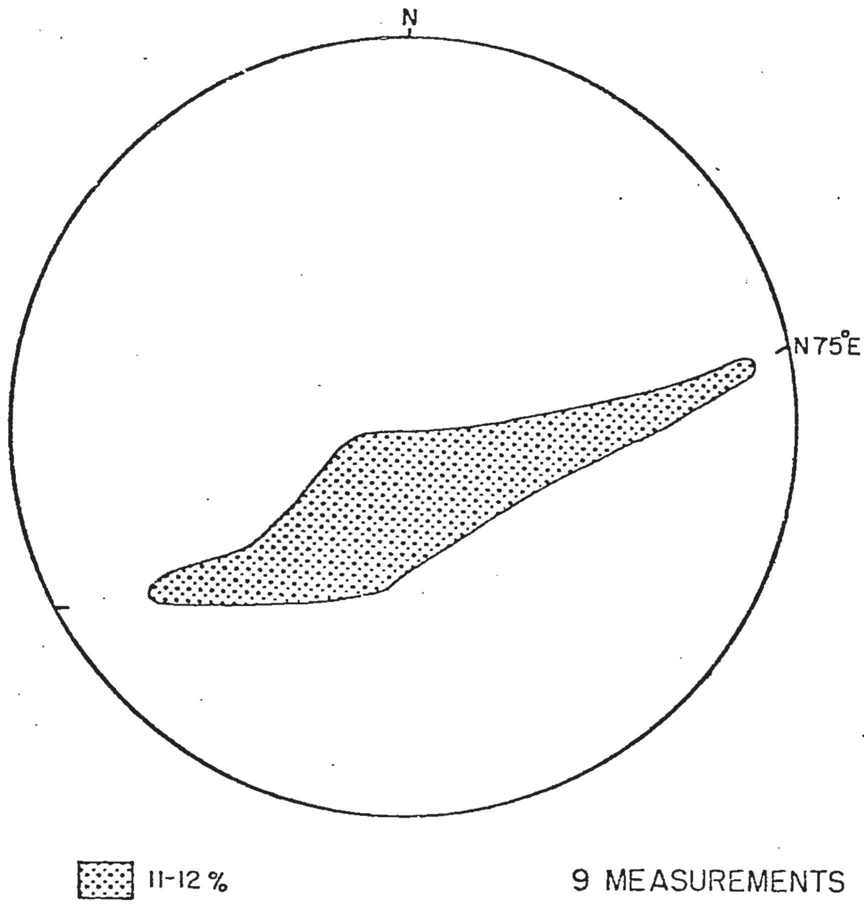


Figure 65: Lower hemisphere equal area projection of lineations (cleavage-bedding intersections) from Spoon Lake structural block. Contour is per 1% area.

Discontinuous structures

Faults

Two major longitudinal faults transgress the present area of study and slice it into three distinct structural blocks (Knife Lake, Spoon Lake, and Kekekabic Lake). The faults trend northeast-southwest, have steep dips (Gruner, 1941; Feirn, 1977), and closely parallel bedding. Hence the total displacement and sense of relative movement along these faults is uncertain. The longitudinal faults are linear within the present study area but become curvilinear to the northeast, where they trend almost due north (Gruner, 1941). Longitudinal as well as transverse faults are generally not apparent or traceable in the field due to the amount of vegetation, lake, and swamp cover. Actual fault contacts are rarely exposed. The longitudinal faults are marked by depressions in the field which are expressed as low, trench-like lineations on aerial photographs.

Longitudinal faults of the present study were plotted on the geologic map (Plate 1) according to Gruner's (1941) map and also by the use of aerial photographs. Field checking of the faults usually resulted in finding "shear zones" where rocks had undergone intense cataclasis. Transverse faults were placed on the geologic map after a study of aerial photographs had revealed lineaments in these areas. Some minor longitudinal faults, not mapped by Gruner (1941), are also included.

The longitudinal fault that separates the Spoon Lake and Kekekabic Lake segments is a linear feature which trends approximately N 70°E over its exposed length (Plate 1). In the present area of study, the fault extends from the portage between Knife and Eddy Lakes (NE1/4, SE1/4, Sec. 20, T. 65N., R. 6W.) to the north shore of Pickle Lake and southwestward beyond the limits of the mapped area. The fault was observed in three areas, one of which is along the south shore of Knife Lake in the SE1/4, SE1/4, SE1/4, of Sec. 19, T. 65N., R. 6W. Here a small shear zone, 20 feet wide, shows a left-lateral displacement of graywacke and slate beds. The horizontal separation is approximately 8 feet and is herein interpreted as representative of the direction of relative fault movement along the longitudinal fault, but not its total horizontal slip as envisioned by Gruner (1941). A fault zone approximately 500 feet wide was observed along the south shore of Sema Lake (SE1/4, NE1/4, Sec. 25, T. 65N., R. 6W.) and consists of a vertical cliff, 40 feet high, composed of highly sheared slate. Similarly, a 20 feet wide fault zone, consisting of sheared graywackes and slates, was noted at the south end of the portage between Spoon and Pickle Lakes.

The longitudinal fault between the Spoon Lake and Kekekabic Lake segments apparently splits in Sec. 26, T. 65N., R. 7W., with the smaller segment trending S 60^{o}W from Dipper Lake to the eastern shore of Pickle Lake.

The other major northeast- to southwest-trending longitudinal fault extends from the SW1/4, of Sec. 24, T. 65N., R. 7W., southwestward to Bonnie Lake. The fault trends N 70^{o}E and was not observed during the field mapping. According to Gruner (1941), this longitudinal fault is defined by highly sheared slate outcrops or valleys and swamps between Bonnie and Knife Lakes, and continues past the northeast and southwest limits of the mapped area.

A minor longitudinal fault was located from a study of aerial photographs between Sema and Pickle Lakes (Plate 1). The fault trends approximately N 70°E and was observed on the west shore of Sema Lake (SE1/4, SE1/4, NW1/4, Sec. 25, T. 65N., R. 7W.). Here a shear zone has an apparent right-lateral horizontal separation of 5 feet. The shear zone contains fault gouge composed of carbonate (Fig. 66).

Figure 66: Fault gouge along longitudinal fault. SE1/4, NW1/4, Sec. 25, T. 65N., R. 7W.

Carbonate associated with shear zones was also noted by Feirn (1977) and Severson (1978). Severson concluded the carbonate can be explained as the result of the influence of CO_2-rich fluids along faults.

Vertical displacement along the major longitudinal faults was estimated by Gruner (1941) to be in the thousands of feet. As mentioned earlier in the petrography, there is a possible stratigraphic correlation of arkose samples between the Knife Lake and Spoon Lake blocks. The arkose of the Spoon Lake block is apparently overlain by graywackes and slates which have been estimated to be 800 feet thick (Plate 2). The arkose of the Knife Lake block is exposed at the surface (Plate 2). This indicates a minimum vertical displacement of 800 feet between the two blocks, the Spoon Lake block apparently moving downward. Gruner (1941) noted that vertical displacement along the longitudinal fault separating the Knife Lake and Spoon Lake blocks may be of different magnitudes at different points along this fault. However, he estimated the greenstone within the Knife Lake block was raised 1000 to 2000 feet with respect to the rocks on the south side of the fault.

A stratigraphic correlation does not exist between the Spoon Lake and Kekekabic Lake blocks. Hence no estimate can be made here as to the vertical displacement between these two blocks. Gruner (1941) stated the movement of the Kekekabic Lake block was downward relative to the Spoon Lake block; the throw near Eddy Lake may amount to 10,000 feet.

Faults which transect the trend of the longitudinal faults and have smaller vertical and horizontal displacements are included in the geologic map shown in Plate 1. One of these transverse faults is located between Sema and Kekekabic Lakes and extends from the SW corner of Sec. 25 to the NE corner of Sec. 36, T. 65N., R. 7W. The other is located between Eddy Lake and the Kekekabic

Ponds and occupies the central portion of Sec. 29, T. 65N., R. 6W. The two transverse faults trend N 70^{O}W and both have an approximate minimum vertical separation of 200 feet (Fig. 30), and a horizontal separation of 250 feet (Plate 1). The vertical separation is based on petrographic and structural analyses of the porphyritic augite-hornblende andesite. The augite-hornblende andesite is estimated to be at least 200 feet thick (Fig. 30); its top is exposed on the west side of the transverse fault between Eddy Lake and the Kekekabic Ponds. To the east, the base of the augite-hornblende is exposed, indicating a vertical separation of at least 200 feet. The horizontal separation was determined by the apparent offset of rock contacts was shown in Plate 1.

Summary of structural features

A summary of the structural features observed during this study, and a possible sequence of folding (F_1, F_2, and F_3) events, prior to faulting, is presented in Tables 12 and 13 for the Kekekabic and Spoon Lake structural blocks, respectively. Structural features observed in the Knife Lake structural block are not presented in this manner since little structural data was obtained from this block. Briefly, the rocks within the Knife Lake block trend N 74^{O}E and dip 60^{O} to the southeast. No reversals in top or dip directions are seen in this block, indicating the rocks are not folded; at least not in the present study area. The five cleavage planes measured within this block trend dominantly N 56^{O}E and dip 69^{O} to the southeast. Only two cleavage-bedding intersections were plotted from this block with one plunging 68^{O} to the

TABLE 12--STRUCTURAL EVENTS OF KEKEKABIC LAKE STRUCTURAL BLOCK

Summary of Structural Events,

Kekekabic Lake Structural Block

Structural Feature	F_1		F_2		F_3 ?		Post-folding	
	Major	Minor (Parasitic)	Major	Minor	Major	Minor	Major	Minor
S_1	deformed bedding into syncline trending N 50° E, plunging 30° SW. (Fig. 58)	one minor fold, sub-horizontal fold axis, steeply dipping hinge surface (Fig. 62)		deformed bedding into S-folds with near vertical fold axes (Plate 1)	warping of beds caused by broad folding, hinge axis trends N 60° W, and axis may lie just west of Seagull Lake (Fig. 3)	?	longitudinal faulting separates Spoon Lake and Kekekabic Lake blocks, fault trends N 70° E	transverse faulting locally offsets rock contacts, faults trend N 70° W
S_2			produced pervasive N 62° E, 77° SE cleavage (Fig. 63)					
L_2			intersection of pervasive cleavage and N 50° E bedding producing lineation trending N 61° E (Fig. 51)					

TABLE 13--STRUCTURAL EVENTS OF SPOON LAKE STRUCTURAL BLOCK

Summary of Structural Events,

Spoon Lake Structural Block

Structural Feature	F_1		F_2		F_3?		Post-folding	
	Major	Minor (Parasitic)	Major	Minor	Major	Minor	Major	Minor
S_1	deformed bedding into syncline trending N 45° E, plunging 35° SW (Fig. 60)	?		may have deformed bedding into S-folds? (Plate 1)	warping of beds caused by broad folding, hinge axis trends approx. N 60° W, and may lie just west of Seagull Lake (Fig. 3)	?	longitudinal faulting separates Spoon Lake and Knife Lake blocks, fault trends N 70° E	?
S_2			produced pervasive N 70° E, 66° SE cleavage (Fig. 64)					
L_2			intersection of pervasive cleavage and N 50° E bedding producing lineation trending N 75° E (Fig. 61)					

south and the other 64^{o} to the southeast.

Interpretation

Having summarized the structural features, folding (F_1, F_2, and F_3) events, and periods of faulting within each of the structural blocks, an attempt is made here to account for all of these in terms of four tectonic deformations, D_1, D_2, D_3, and D_4. D_1 is here considered to be the oldest and D_4 the youngest. The four tectonic deformations are here developed without regard to the Knife Lake structural block.

The first period of deformation (D_1) produced open to isoclinal folds within the sedimentary rocks along northeast-trending axes. The folds produced have subhorizontal fold axes with vertical to overturned hinge surfaces which plunge to the southwest. The folds are defined by reversals in top directions of graded graywacke beds. One parasitic fold, presumably produced during D_1, was observed in outcrop. The plunge of the fold axes of this fold is subhorizontal.

A later tectonic deformation (D_2) produced the N 62^{o}-70^{o}E trending S_2 cleavage which is predominant in both the Spoon Lake and Kekekabic Lake blocks. The slight variation in cleavage orientation between the Spoon Lake and Kekekabic Lake blocks may be related to movement of the blocks during broad folding and/or longitudinal faulting. The D_2 deformation apparently deformed the limbs of the D_1 folds, producing S-folds with vertically-plunging fold axes. In addition, the buckled appearance of the porphyritic hornblende volcanic body within the Kekekabic Lake block may also be related to the D_2 deformation.

Following D_2, a third deformation (D_3) apparently produced a very broad fold which warped the rocks within the eastern Vermilion district. The fold axis of the fold trends approximately N 60^{o}W, and the axis may be located just west of Seagull Lake (Fig. 3). Evidence for this broad folding can be seen in Gruner's (1941) map and also in the structural (cleavage) data compiled by Severson (1978) and Duex (pending completion).

Faulting (D_4) occurred on a regional scale with major longitudinal faults dividing the eastern Vermilion district, including the present study area, into discrete structural blocks. The longitudinal faulting is assumed (Sims, 1972) to have been contemporaneous with the diapric rise of the granitic batholiths that enclose the Vermilion district. The longitudinal faults within the present area of study trend N 70^{o}E. Concurrent or subsequent to regional faulting, transverse faulting locally offset rock contacts. The transverse faults of this study trend N 70^{o}W.

SUMMARY and CONCLUSIONS

Geologic History of the Kekekabic Lake Area

Development of the rocks within the Kekekabic Lake area commenced with the deposition of mafic (basalt or andesite) crystal tuff detritus eroded from the flanks of a volcanic pile. The tuffaceous sediment was deposited in a moderate to deep water basin building up a volcaniclastic deposit 250 feet thick, which is exposed in the Knife Lake greenstone segment and herein called arkose, after Gruner (1941).

Arkose was deposited subsequent to the formation of older members of the Knife Lake Group which lie unconformably on the Saganaga batholith. The batholith intruded greenstone and pre-Knife Lake Group sedimentary rocks of the eastern Vermilion district, but was rapidly unroofed to provide some detritus to the Knife Lake Group (e.g., McLimans, 1971, 1972; Ojakangas, 1972a, 1972b; Severson, 1978).

Arkose formation was followed by deposition of lithic and feldspathic graywackes, slates, mafic to felsic crystal tuffs, conglomerate, and very minor iron-formation which comprise the Amoeba Lake member of the Knife Lake Group. The rocks within this member were studied in both the Spoon Lake and Kekekabic Lake segments and comprise a sedimentary sequence which is at least 1800 feet thick.

Lithic graywackes of this member consist predominantly of andesite, dacite, basalt, and rhyolite rock fragments which were presumably eroded from mafic to felsic subaqueous to subaerial flows and hypabyssal rocks within a volcanic pile accumulation. Spasmodic periods of explosive volcanism deposited mafic to felsic crystal tuffs on the slopes of volcanic piles and also directly into the basin. The tuffaceous material on the unstable slopes of the volcanic piles was deposited as feldspathic graywackes. Ferruginous slates associated with plagioclase-rich tuff deposits were presumably formed by chemical precipitation during exhalative volcanism (Goodwin, 1962).

Graywackes were deposited by turbidity currents on the depositional lobe of the mid-fan region of a submarine fan such as modeled by Walker and Mutti (1973). The turbidity currents flowed into a moderate to deep water basin since ripple marks and cross-bedding, indicative of shallow agitated water, are absent in the graywackes studied. In addition, the angular shape of the volcanic rock fragments indicates the graywackes were not reworked in a shallow-water environment. The graywackes are separated by muddy interbeds which may represent the pelagic and hemipelagic facies of Walker and Mutti (1973). These facies are associated with the basin floor of an idealized slope-fan-basin floor system within a depositional basin. Deposition of a muddy interbed, which may have required hundreds or thousands of years (Ojakangas, 1972a), was interrupted by short-lived turbidity currents.

Sedimentation of material derived by the erosion of volcanic piles was followed by a major period of extrusion during which three distinct subaerial flows were deposited. Basaltic to andesitic lava flowed over the surface of the underlying graywackes, slates, tuffs, conglomerate, and iron-formation on three different occasions producing a volcanic sequence at least 800 feet thick. Variations in color, phenocryst type, and chemical composition delineate the three flows. The presence of amygdules and hexagonal cooling columns indicate the flows are subaerial. Sufficient time existed between periods of extrusion to allow the formation of volcanic "sedimentary" breccias which are composed almost entirely of clasts derived from these flows.

Extrusion of the three subaerial flows was followed by fluvial transport of a hornblende-rich tuff, presumably deposited on the slopes of a volcanic pile which was located to the southeast of the Kekekabic Lake area. The tuff is a tholeiitic basalt in chemical composition and consists of 60 percent hornblende crystals, 1 percent augite crystals, 25 percent matrix and 14 percent alteration product (muscovite). The hornblende-rich tuff is at least 200 feet thick at the western end of the map area, and contains agglomerate clasts. The agglomerate clasts are accidental lamprophyre rock fragments which were presumably derived from lamprophyre dikes such as those that were cogenetic with the Snowbank and Saganaga batholiths (Sundeen, 1936). The three subaerial flows and tuff and agglomerate comprise the Kekekabic Lake member of the Knife Lake Group (Gruner, 1941).

Fluvial transport of the hornblende-rich tuff was followed by intrusion of porphyritic plagioclase-bearing dikes which range from diorite to syenodiorite in composition. These dikes are found in the Kekekabic Lake segment and are presumably a later phase of the Kekekabic stock (Stark, 1927) which was emplaced along the south shore of Kekekabic Lake.

After an unknown period of time, the rocks of the Kekekabic Lake area were isoclinally folded on southwest-trending axes. The folding apparently occurred as a result of the diapiric rise of the Vermilion and Giants Range batholiths to the north and south, respectively, of the Vermilion district (Sims, 1972). The isoclinal folds are found in the Spoon Lake and Kekekabic Lake segments, trend S 45°-50° W, have vertical to overturned hinge surfaces, and plunge to the southwest. Subsequent to this a second period of deformation produced the pervasive N 62°-70° E cleavage seen in both the Spoon Lake and Kekekabic Lake segments. In addition, the rocks within the limbs of the isoclinal folds were deformed into S-folds during this second deformation while the shape of the porphyritic volcanic body, contained in the Kekekabic Lake segment, was deformed. A third period of deformation produced broad folding which warped the beds of the eastern Vermilion district on an axis trending approximately N 60° W. This axis may lie just west of Seagull Lake.

During or subsequent to diapirism, but after folding, the rocks within the Kekekabic Lake area were faulted into three distinct segments by two longitudinal faults. The longitudinal faults trend N 70° E. During longitudinal faulting the Spoon Lake segment was dropped approximately 800 feet relative to the Knife Lake greenstone segment. Vertical separation between the Spoon Lake and Kekekabic Lake segments was not estimated in this study, but Gruner (1941) stated the throw between the Kekekabic Lake and Spoon Lake segments may be on the order of 10,000 feet in the vicinity of Eddy Lake.

A second period of faulting, either concurrent or subsequent to longitudinal faulting, produced transverse faults which trend N 70° W, have apparent vertical separations of 200 feet, and apparent horizontal separations of 250 feet.

Rocks of the Kekekabic Lake area were intruded on two separate occasions by diabase dikes of Keweenawan age (Stark, 1927). The freshest, and therefore presumably the youngest, diabase is found in the Spoon Lake segment. The more heavily altered, or oldest, diabase is found in the Kekekabic Lake segment. The effects of the major Keweenawan intrusions to the south of the present area are unknown.

The topography of the Kekekabic Lake area was eroded and lowered for a large interval of time until Pleistocene ice sheets of the Rainy Lobe (15,000 years ago) invaded the area. The ice sheets deposited little glacial material, but did scour and smooth the rock surfaces.

Conclusions

Significant conclusions which can be drawn from this study include:

1) The hornblende andesite body mapped by Gruner (1941) is actually a composite volcanic unit consisting of three subaerial flows; they include: a) a green porphyritic augite-hornblende andesite at the contact with the underlying graywackes and slates of the Amoeba Lake member of the Knife Lake group; b) a red porphyritic hornblende andesite that lies conformably above the augite-hornblende andesite; and c) a green porphyritic hornblende

basalt that lies conformably above the red hornblende andesite. All three subaerial flows were deformed along with the underlying graywackes and slates into a syncline which encompasses the entire Kekekabic Lake segment.

2) The Kekekabic Lake area is representative of the middle portion (andesite to dacite) of the regional Lower Precambrian volcanic-sedimentary pile of the eastern Vermilion district. Sedimentary rocks within the area developed in a basin of moderate depth which was flanked by an island arc or continental orogenic belt. The basin apparently was filled prior to the extrusion of the basalt-andesite flows since the flows within the composite body are subaerial and show no signs (i.e., pillowed flows with devitrified glassy rinds) of deposition in water.

3) Two periods of deformation have occurred in the Kekekabic Lake area, as well as broad folding and longitudinal and transverse faulting. The first period of deformation isoclinally folded the volcanic and sedimentary rocks within the area on S 45°-50° W-trending fold axes. The folds produced have subhorizontal fold axes with vertical to overturned hinge surfaces. The second deformation produced S-folds in the limbs of the isoclinal folds, deformed the composite volcanic body, and produced the pervasive N 62°-70° E cleavage seen throughout the area. Broad folding on an axis trending N 60° W warped the beds of the eastern Vermilion district as can be seen on Gruner's (1941) map. The axis of this broad folding may lie just west of Seagull Lake. The vertical separation along the longitudinal fault, which trends N 70° E, between the Spoon Lake and Knife Lake segments is estimated to be

800 feet. The vertical separations along the two transverse faults, which trend N 70° W, are 200 feet, and the horizontal separations are 250 feet.

4) Agglomerate clasts within the hornblende-rich tuff and agglomerate were not derived from the composite volcanic body as assumed by Gruner (1941). They are accidental lamprophyre rock fragments that were presumably derived from lamprophyre dikes such as those associated with the Snowbank and Saganaga batholiths.

5) Graywackes within the Kekekabic Lake area are largely volcanogenic in origin. The framework material is almost entirely derived from subaqueous to subaerial flows, hypabyssal rocks, and tuff deposits. Plutonic framework material, presumably derived from the Saganaga Tonalite, comprises a very minor component of the graywackes studied. Mafic (basalt or andesite) and felsic (trachyte to latite) crystal tuffs, which are interbedded with the graywackes, were apparently deposited directly into the basin. Turbidite sequences, indicative of turbidity currents possibly generated by the mass movement of volcanogenic debris down the slopes of volcanic piles, are noticeably absent between tuff beds.

6) Turbidite sequences of the Kekekabic Lake area correspond to facies associated with the depositional lobe of the mid-fan portion of a submarine fan (Walker and Mutti, 1973). Bedding characteristics within the graywacke-slate outcrops studied are similar to those described by Walker (1967) for distal turbidites.

7) The structural blocks within the Kekekabic Lake area are petrographically distinct in terms of gross lithologies (e.g., arkose vs. graywacke) and variations in lithologies (e.g., some

types of rock fragments found in the lithic graywackes of the Spoon Lake segment are not found in the lithic graywackes of the Kekekabic Lake segment). In general, graywackes of the Kekekabic Lake segment contain a higher percentage of K-feldspar and hornblende grains than those of the Spoon Lake segment. In addition, lithic graywackes of the Kekekabic Lake segment contain hornblende andesite, hornblende trachyte-latite-trachyandesite, and polycrystalline hornblende rock fragments while the lithic graywackes of the Spoon Lake segment do not. Plutonic rock fragments are found in the lithic graywackes of the Kekekabic Lake segment while chert rock fragments are found in the lithic graywackes of the Spoon Lake segment.

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